THE UNIVERSITY OF ALBERTA.

A STUDY OF SHRINKAGE OF SOIL-CEMENT

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE.

DEPARTMENT OF CIVIL ENGINEERING

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SEPTEMBER 20, 1961.

ABSTRACT

In recent years the use of soil-cement as a highway base course material has become increasingly popular. A considerable amount of research has been carried out to investigate the physical properties of this material, particularly from the aspect of strength and durability. The shrinkage of soil-cement has not received too much attention in the research field since it is felt by many engineers that shrinkage cracks are not detrimental to the structural ability of the material as a base course. With increasing demands for highways of higher load carrying capacity under all subgrade conditions, the significance of shrinkage cracking is receiving more attention. In the Province of Alberta, soil-cement which has been used as a base course has not been in service long enough for a complete evaluation. However, the results of a current evaluation programme indicate that shrinkage cracks in the base course do reduce the load carrying capacity of the highway.

This thesis presents the results of a laboratory investigation of shrinkage of soil-cement made from three Alberta sandy soils. The soils, which were investigated, have been used for soil-cement projects within the province. The effect of variations in cement content, initial

moisture content, density and curing conditions were investigated. It was found that the greatest amount of shrinkage occurred in the finest soil, and the least in the coarsest soil. For each soil-cement, the four variables affected shrinkage in different ways. The most significant variable for the finest sand investigated was the initial moisture content; for the medium sand it was cement content; for the coarse sand it was density.

There are very few references to shrinkage of soil-cement contained in the literature. On the other hand, the volumetric change characteristics of concrete have received considerable attention. By direct analogy with what is known of the shrinkage of concrete, the shrinkage characteristics of soil-cement can be better understood. By using this analogy, a possible explanation of the various trends exhibited by each soil-cement which was investigated is given.

In addition, the observations of shrinkage cracking of two field projects are given. The field data was insufficient to relate to the laboratory results. The most significant factor, which was observed to affect shrinkage of soil-cement in the field, was the quality of the seal coat. The least shrinkage occurred where a non-penetrating asphaltic membrane was formed.

Recommendations are made for further study.

ACKNOWLEDGEMENTS

The author would like to express his sincere appreciation to:

Professor E.L. Fowler for his helpful suggestions and constructive criticism of this thesis;

The Alberta Joint Highway Research Programme, under whose sponsorship this study was carried out;

Mr. B.P. Shields and Mr. B.G. Hutchinson for their interest and advice. Special thanks is due to Mr. B.G. Hutchinson for assisting the author in obtaining much of the reference literature on soil-cement;

Professor S.R. Sinclair for his advice on the manner of presentation of the data;

Mr. H. Alton for his assistance in carrying out the laboratory programme and the field investigation;

The Department of Highways of Alberta for providing the soil and their laboratory design data.

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CHAPTER I

INTRODUCTION

SOIL-CEMENT AS A CONSTRUCTION MATERIAL

Soil-cement is a highly compacted mixture of soil, water and Portland cement. As the cement hydrates, this mixture results in a hard durable material of construction.

The most extensive use of soil-cement in North America has been as a base course material for highways, streets and runways. To a lesser extent, soil-cement has been used for lining canals, ditches and water reservoirs as well as for low cost rammed in place and block buildings.[1]

In recent years the province of Alberta has undertaken several highway projects for which soil-cement was used as a base course material. Since 1959 approximately 150 miles of highway using soil-cement have been constructed. During this period, the Department of Highways in conjunction with the Alberta Research Council and the University of Alberta, have initiated considerable research to investigate the problems associated with soil-cement in the Province of

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[1]Felt, E.J.,"Status of PCA Soil-Cement Development" Journal of the Research and Development Laboratories,Portland Cement Association. Vol.3, No.1.Jan.1961. p.7.

Alberta.

The characteristics of almost any soil can be modified by the addition of a small amount of cement. Soils which are so treated are known as cement-modified soils. As the cement content is increased, instead of a modified soil, the material is changed to a soil-cement having its own unique properties.

In discussing the physical relations of soil and soil-cement mixtures, M.D. Catton made the following observations:

> "It has been pointed out repeatedly that the lower cement contents may change the soil characteristics but as cement contents are increased, a condition is reached where the addition of more cement changes the material from a different soil to a structural material."[2]
> (Italics in the original).

Catton explained the structure of soil-cement as follows:

> "Study of soil-cement mixtures in the laboratory and field indicates that each cement grain picks up a varying number of soil grains (depending on the grain size of the soil) and as the cement hydrates and crystallizes, a new and larger soil grain or agglomeration

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[2]Catton, M.D.,"Research on the Physical Relations of Soil and Soil-Cement Mixtures."Highway Research Board Proceedings, Vol.20,1940. p.854.

is produced. As more and more cement is added, more soil grains lose their identity to become larger soil grains or agglomerations. The agglomeration of cement and soil grains is shown by the tests of soil-cement mixtures of low cement content. These agglomerations of cement grains and soil grains can also be thought of as links in a chain and when enough cement has been added to link all agglomerations together, with pockets of trapped soil, the mixture becomes a structure material, rather than a soil."[3]

The physical properties of soil-cement are influenced by many variables. The physical-chemical characteristics and gradation of the soil itself are of utmost importance. In addition to the soil effects, research has shown that a number of other factors have a major influence on the properties of the soil-cement. These factors are: cement and mixing water content, the length of mixing time, the compacted density of the material, the method of curing, and the age and moisture content of the soil-cement when it was tested.[4]

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[3]Ibid.

[4]Felt, E.J., Op. Cit p.8.

Soil-cement for use as a highway base course is usually designed to meet specified minimum standards of performance on the basis of compressive strength and durability. Testing is carried out using standardised soil preparation and testing techniques.

It has been found that for several soils encountered in Alberta, if the soil-cement mixture meets the minimum compressive strength requirements, it will also meet the requirements specified for durability.[5]

Since soil-cement was first introduced as a material of construction in the United States, its properties have been subjected to rigorous investigation, both in North America and abroad. The physical property which appears to have received the least attention in laboratory investigations and field evaluations, is that of the volume change characteristics.

THE INTENT OF THIS REPORT

The intent of this report is to present the results of a study of the factors affecting shrinkage in soil-cement

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[5] Domaschuk, L., "An Investigation of the Stabilization of Several Sands and a Sandstone From Alberta Using Portland Cement." Master thesis (unpublished). University of Alberta, 1960.

produced from three Alberta soils. All three soils have been used for soil-cement projects within the province.

Although there has been very little published which deals directly with shrinkage of soil-cement, there is a large amount of literature available on the shrinkage characteristics of concrete. Therefore, in addition to a review of the literature on shrinkage of soil-cement, a chapter is devoted to the shrinkage of concrete. This has been done to show where shrinkage of soil-cement is analogous to that of concrete and, where it is not.

In this report, emphasis is placed upon the shrinkage characteristics of soil-cement resulting from the inherent properties of the material and from moisture losses. In addition, an attempt is made to qualitatively correlate the laboratory results with the performance of the material in place as a highway base course.

CHAPTER II

SHRINKAGE IN SOIL-CEMENT
A REVIEW OF THE LITERATURE

At the 1952 conference on soil stabilization held at the Massachusetts Institute of Technology, M.D. Catton made several observations on shrinkage cracking, which perhaps more than anything else, have influenced the present day attitude of engineers toward this phenomena. Catton observed, that both in the laboratory and in the field, the volume decrease in soil-cement which takes place during cement hydration and hardening, is usually greater than subsequent increases in the field produced by increases in moisture and temperature. Moreover, according to Catton, the experienced soil-cement construction engineer watches impatiently for contraction cracks to appear for reassurance that he is producing hard soil-cement.[1] Catton also observed that the cracks did allow surface water access to the subgrade which was usually weaker when wet than when dry. However, the service records of soil-cement roads, which were designed for lighter traffic, showed clearly that there was no

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[1] Catton, M.D., "Soil-Cement: A Construction Material." Proc. of the Conference on Soil Stabilization, Mass. Inst. of Technology, 1952. p. 35.

structural breakage under the more adverse subgrade conditions. This performance was accredited to the interlock of adjoining slabs plus the distribution of loads over an appreciable area due to slab action.[2]

In a study of several soil-cement base courses on military airfields in the U.S.A., J.F. Redus observed that cracks occurred in all pavements examined, usually forming rectangular patterns of varying size, both in areas untouched by traffic and in well travelled areas. These cracks were reflected from the soil-cement base course through the asphaltic concrete surface. Redus concluded that the cracking was caused by shrinkage of the soil-cement and not by overloading. He further observed that the cracks appeared to have no effect on the ability of the soil-cement to carry the imposed loads, nor on the durability of the soil-cement mixture.[3] In a discussion of the same paper, E.J. Robbins of the Portland Cement Association observed that Redus' study confirmed that reflection cracking of soil-cement base courses through the bituminous surface is not associated with structural failure. Rather cracking is a function of the

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[2]Ibid. p. 36.

[3]Redus, F.J., "Study of Soil-Cement Base Courses on Military Airfields." 37th Annual Meeting, Highway Research Board. Jan. 1958. HRB Bltn. 198. p. 15.

drying and hardening of the base.[4]

The above references would lead one to believe that shrinkage cracking in soil-cement is not detrimental to the structural ability of the material but rather is an indication of high quality. In spite of the dearth of published work concerning this aspect of soil-cement, there is sufficient information in the literature to cast some doubt on the significance of shrinkage.

T.J. Marshall of Australia has published the only reference known to the writer in which shrinkage in the field has been measured quantitatively.[5] Table 1 is a reproduction of Marshall's work.

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[4]Ibid. p. 19.

[5]Marshall, T.J., "Some Properties of Soil Treated with Portland Cement." Symposium on Soil Stabilization (Australia) Jan. 18-22 (1954) p. 30.

TABLE 1

Size distribution of Cracks in soil-cement pavements at Roto and North Bourke (Australia). As Reported by T.J. Marshall.

Width of Crack (in 48ths inch)	No. of cracks in 48 lin. feet of Runway Surface					
	Roto, 84° runway		Roto, 2° runway		N. Bourke, 135°	
	At 1150′	At 3050′	At 2000′	At 5000′	At 5280′	At 1500′
<1	74	60	91	100	31	40
1	18	24	26	19	15	27
2	17	6	11		18	10
3	13	5	2		5	4
4	1	3			3	3
5					5	22
6					2	0
7					0	1
8					1	
Time since processing (days)	77	70	41	32	46	33
Ave. field density as % of Proctor Maximum	86	93	90	95	85	91
Lineal shrinkage %	+0.44	0.30	0.30	0.19	0.48	0.37

\+ Calculated from the above frequency distribution assuming cracks smaller than 1/48" to be 1/3 x 1/48"

From the result of his study at two airports, Marshall observed a relationship between density and shrinkage. For each runway which was investigated, the higher density is related to the lower shrinkage. The crack patterns were noted to develop strongly during the first week.

In the field of soil-cement, it is a well-known fact that for a given mix of soil-cement, the density has a great influence on strength. With a relatively small decrease in density, there can be a very large decrease in strength. Therefore, according to Marshall's study, the appearance of shrinkage cracks in soil-cement might be an indication of low density and thus low strength rather than a hard soil-cement, as suggested by Catton.

Some of the earliest work with soil-cement as a highway base course material was carried out in California. E. Withycombe of the California Division of Highways has reported that the volume change characteristics of the soil-cement was instrumental in arriving at a specified design strength for the finished product.[6] In the early stages of cement base construction, high cement contents were

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[6]Withycombe, E., "Base Stabilization with Portland Cement." Proc. Fifth Calif. Street Highway Conference, Univ. of Calif., The Institute of Transportation and Traffic Engineering, Berkely, California, Feb. 4-6, 1953, p. 34.

specified and it was not unusual for the material to develop twenty-eight day strengths of 2,000 to 3,000 pounds per square inch. Such mixtures, containing high cement contents, were susceptible to excessive volume changes which resulted in reflection cracking and unsightly surface spalling. It was subsequently decided that a strength of 650 pounds per square inch at seven days was the point where the cement content was low enough so that cracking ceased to be objectionable. Specifications were drawn up accordingly.

These observations by Withycombe indicate that cement content is an important factor influencing the shrinkage of soil-cement. However, opposite trends were observed in other areas of the United States.

Much of the pioneering work on soil-cement in North America was carried out in South Carolina. Reporting on an experimental base course, E.A. Willis observed that as the amount of cement was increased, the amount of shrinkage cracking decreased.[7] Differences in the amount of cracking for mixtures with the same cement content were accredited to probable variations in the soil.

On the same experimental road, it was also found that the type of curing compound used on the soil-cement had an

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[7]Willis, E.A., "Experimental Soil-Cement Base Course in South Carolina." Public Roads. Vol. 25. No.1.

appreciable influence on the amount of cracking which occurred.[8] Where tar was used as a curing aid, cracking occurred in an amount and intensity which was equal to cracking in a similar compacted mixture which had received no curing aid. Shrinkage cracking did not occur in the base courses where emulsified asphalt was used as a curing aid. Where the tar was used, it penetrated the surface to a depth of one-quarter to one-eighth inch and dried quickly; whereas the emulsion formed a film over the surface and did not dry for about three days. For both curing aids the surface of the soil-cement was kept in a moist condition until the curing aid was applied.

The extent of shrinkage cracking which was reported by Withycombe and Willis was not recorded quantitatively. It is possible that the number of cracks was related to the strength of the soil-cement more than to the volumetric change characteristics. A soil-cement having a high cement content and therefore a high compressive strength might form cracks at greater intervals but actually undergo more shrinkage as indicated in the width of the crack. It does, however, appear that an opposite trend in the relationship between cement content and shrinkage as reported by Withycombe, is indicated in Willis' work.

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[8] Ibid.

A laboratory investigation of means of reducing shrinkage in compacted soils by the use of cement, has been carried out in India and was reported by S.R. Mehra and H.L. Uppal.[9] In this investigation, four soils were subjected to tests to determine volumetric shrinkage with increasing cement content. The soils were: a sandy loam, a silty loam, a silty clay loam and a loam. With the untreated soils, it was found that shrinkage increased proportionally as moisture at compaction was increased, up to the optimum moisture content of the soil. Beyond the optimum moisture, shrinkage increased abruptly except in the case of the silty loam. Shrinkage of the silty loam maintained a proportional increase with the moisture content above optimum.

The same four soils were compacted at optimum moisture content with increasing percentages of cement. The volume of the compacted blocks was determined at the time of compaction, after curing for seven days, and after drying in the oven at 105°C to 110°C. Table 2 is a reproduction of the results obtained from this series of tests.

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[9]Mehra, S.R., and Uppal, H.L., "Use of Stabilized Soil in Engineering Construction. Section IV-Shrinkage of Compacted Soils," Journal of the Indian Roads Congress (India), Vol.15, No.2, Nov. 1950, p. 320-335.

TABLE 2

Showing effect of increasing percentage of cement on the shrinkage of compacted soil. As Reported by S.R. Mehra and H.L. Uppal. (India).

SOIL	Percent Optimum Moisture	Percentage Cement used.	Density	Volumetric Shrinkage Percentage
1. Sandy Loam	13.0	0	1.91	0.96
	13.0	2.5	1.88	0.66
	14.0	5.0	1.88	0.61
	14.0	7.5	1.88	0.50
	14.0	10.0	1.87	0.46
	14.0	20.0	1.87	0.37
2. Silty Loam	12.0	0	1.71	0.95
	12.0	2.5	1.70	0.66
	13.0	5.0	1.69	0.55
	13.0	7.5	1.69	0.51
	13.0	10.0	1.69	0.51
	13.0	20.0	1.66	0.47
3. Silty Clay Loam	12.0	0	1.84	2.54
	12.0	2.5	1.82	1.74
	12.0	5.0	1.81	1.42
	13.0	7.5	1.78	1.31
	13.0	10.0	1.76	1.11
	14.0	20.0	1.74	0.96
4. Loam	12.0	0	1.95	1.23
	12.0	2.5	1.91	0.75
	13.0	5.0	1.89	0.69
	13.0	7.5	1.88	0.66
	13.0	10.0	1.88	0.52
	13.0	20.0	1.87	0.51

From these results it can be seen that shrinkage of the compacted soils decreased as the percentage of cement was increased. Even at twenty percent cement content some shrinkage still existed. It can also be seen that as little as two and one-half percent cement content decreased shrinkage between thirty and forty percent for all four soils.

In another reference to a laboratory investigation of shrinkage, E.J. Felt reported that for silt-clay soil-cement mixtures, soil type is first in importance and initial water is second in governing drying shrinkage.[10] He further reported that cement content and density of a particular soil-cement had only a minor effect on shrinkage when compared to soil type and initial moisture content.

Thus a review of the literature reveals that shrinkage in soil-cement may or may not be detrimental to its performance. The references to the various factors which may affect shrinkage are somewhat vague and very conflicting.

THE PROBLEM OF SHRINKAGE CRACKING

There are presently many different opinions on whether or not shrinkage cracks in highway soil-cement base

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[10] Felt, E.J., Op.Cit. p.14.

courses are detrimental to the structural ability of the highway. In order to solve this problem, and to obtain answers for many other questions, the Alberta Research Council in co-operation with the Alberta Department of Highways, is presently conducting a field evaluation of soil-cement base courses constructed in previous years. This programme includes a study of deflections under load at shrinkage cracks, compared to deflections which occur in uncracked sections. Although there is insufficient data from which definite conclusions can be derived at this time, there is an indication that shrinkage cracking does impair the structural ability of the base course.

It appears obvious that with increasingly heavy truck traffic and increasing wheel loads, there will be an increasing demand for highways which are structurally sound under the most adverse conditions. If shrinkage cracking proves to be detrimental to the structural performance of soil-cement as a base course, then it must be controlled if soil-cement is required to meet this demand.

CHAPTER III

SHRINKAGE OF CONCRETE

During the past several decades, there have been many investigations carried out to study the factors which affect volumetric changes in concrete. The results of the investigations have appeared periodically in the technical literature. The volumetric change characteristics of concrete are generally understood by engineers.

Although soil-cement is a material of construction, having its own properties distinct from those of concrete, many of these properties can be better explained and understood by developing direct analogies with the corresponding properties of plain concrete. For this reason, Chapter III will be devoted to a brief review of the literature concerning shrinkage in concrete.

CAUSES OF VOLUMETRIC CHANGES IN CONCRETE

Volume changes which occur in concrete are caused primarily by one or more of the following factors:-[1]

(1) Settlement of the fresh mass (bleeding).

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[1] Troxell, G.E. and Davis, H.E. - Composition and Properties of Concrete - McGraw Hill, New York, 1956, p. 228.

(2) Chemical combinations of the cement with water.

(3) Combinations of high alkali cements with reactive aggregates.

(4) Changes in moisture content.

(5) Changes in temperature and humidity.

(6) Applied loads.

Concrete will shrink when it is dried and will expand when it is wetted again. Often the term volume change refers only to the effect of moisture changes.[2]

Since this investigation is concerned with shrinkage in soil-cement, only those factors which could conceivably be extended to soil-cement, will be discussed. This includes (2), (4) and (5) from above.

SHRINKAGE RESULTING FROM THE CHEMICAL COMBINATION OF CEMENT AND WATER

It is now generally accepted that cement after hydration consists of crystalline material plus a calcium silicate gel which results from the combination of cement and water.[3] The amount of gel increases with the age of hydration. For a given amount of cement and for a given

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[2]Ibid.

[3]Ibid. p. 229.

length of time, the amount of gel is greater for higher water/cement ratios and for finer cements. The amount of gel also depends upon the chemical composition of the cement. Fully hydrated dicalcium silicate is believed to be mostly gel whereas tricalcium silicate is more than half gel. For the water-cement ratios which are generally used in average concrete, the gel has a larger volume than the crystalline portions.[4]

Volume changes which are self produced by the hydration of cement are called "autogenous" volume changes.[5] Such volume changes are produced by cement hydration and may result in expansion or shrinkage depending upon the relative importance of the following:[6]

(1) The expansion of new gel resulting from the absorption of free water.

(2) The shrinkage of the gel resulting from the extraction of water from the gel by unhydrated cement.

When the cement paste in concrete has set, the solids

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[4]Ibid.

[5]Davis, H.E. "Autogenous Volume Changes of Concrete" Proc. ASTM Vol.40. (1940) p. 1103.

[6]Washa, G.W. "Volume Changes and Creep". ASTM Special Technical Publication No. 169. (1956) p. 118.

in the paste form a porous structure containing free water. Expansion will occur within the solid mass when the free water is used to form solid hydration products and to expand the gel. Contraction occurs after the free water has been used. The unhydrated cement then removes loosely held water from the gel, which causes the gel to shrink.[7]

DRYING SHRINKAGE OF CONCRETE

Drying shrinkage in concrete is believed to be caused primarily by the contraction of the calcium silicate gel due to moisture losses.[8] The amount of shrinkage due to moisture losses is mainly influenced by the composition and fineness of the cement, the cement and water contents, the type and gradation of the aggregate and humidity and temperature conditions.

Other factors which will affect both shrinkage and expansion to a lesser degree include admixtures, the size and shape of the specimen and reinforcement.[9]

The first four of these factors will be discussed individually as they affect drying shrinkage.

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[7]Troxell and Davis. Op. Cit. p. 230.

[8]Washa. Op. Cit. p. 120.

[9]Troxell and Davis. Op. Cit. p. 232.

(1) The Effect of Composition and Fineness of Cement.

The most significant component of the chemical composition of cement as it affects shrinkage appears to be C2S. The higher the C2S content the greater the contraction in air.[10] There is also an indication that contraction of mortar on drying is increased by an increase in ignition loss. The fineness of cement does not appear to appreciably affect the contraction of concrete in air.

(2) The Effect of Type and Gradation of Aggregate.

The relative compressibility of the aggregate particles appears to be the most important factor resulting in different aggregates causing concrete to have different shrinkage properties.[11] Although the shrinkage of concrete is only a fraction of that of neat cement, tests have shown that if the aggregate were readily compressible, the concrete would shrink as much as neat cement.[12] The ability of normal aggregates to resist shrinkage of the cement paste in concrete depends upon: (1) the extensibility

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[10] Ibid.

[11] Carlson, R.W. "Drying Shrinkage in Concrete as Affected by Many Factors." ASTM Proc. 41st Annual Meeting. V. 38. part II. (1938) p. 436.

[12] Ibid. p. 423.

of the paste, (2) the compressibility of the aggregate and (3) the volume change of the aggregate as it dries.

The grading of the aggregate also affects the shrinkage of concrete. Aggregates which are well graded and have a low void space require less cement paste than poorly graded aggregates. Well graded aggregates which have a large maximum size shrink less because they require lower water contents and less paste and because the cement paste cracks between the large size particles.[13] Tests have shown that when the aggregates exceed about one-quarter of an inch in size, cracking begins. For aggregate sizes less than one-quarter of an inch, there appears to be no internal cracking.[14]

(3) The Effect of Cement and Water Contents.

The largest single factor influencing cement paste and concrete shrinkage is probably the water content. For cements which have normal shrinkage characteristics, an increase in the percentage of water content results in an increase in shrinkage about double the percentage increase in water.[15]

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[13] Washa, G.W. Op. Cit. p. 121.

[14] Carlson, R.W. Op. Cit. p. 424.

[15] Ibid. p. 436.

If the cement content is increased, shrinkage will increase in most concretes. However, if the water content is kept uniform as the cement is increased, the shrinkage will not be greatly increased since the lowering of the water cement ratio offsets the increase in cement content.[16] In general, the effect of increasing cement content is relatively minor in comparison to increasing the water content.

(4) <u>The Effect of Temperature and Humidity</u>.

A change in the humidity of the air, in which concrete is curing without a curing aid, affects drying shrinkage inasmuch as it affects the rate of moisture loss. If the concrete dries slowly, hydration will progress with shrinkage. Therefore, the gel structure will grow and become more resistant to tensile stresses.

Shrinkage in dry air can be retarded by a curing aid which will reduce moisture losses. Tests have shown that specimens coated with tar after thirteen days water curing and one day air drying, shrank one-twentieth as much as specimens which had no curing aid but which were prepared and stored in similar conditions for the same length of time.[17]

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[16] Troxell and Davis. Op. Cit. p. 238

[17] Ibid.

It appears that the higher the preliminary curing temperature, within the range from 70° F to 150° F, the less the subsequent drying shrinkage. High pressure steam curing practically eliminates drying shrinkage.[18]

SHRINKAGE RESULTING FROM CHANGES IN TEMPERATURE AND HUMIDITY

The thermal volume change characteristics of concrete is similar to other materials of construction. A commonly used average value of the thermal coefficient of expansion within the normal range of temperatures is 5.5 millionths per degree Fahrenheit.[19]

Under given conditions of drying, concrete will eventually reach equilibrium with respect to shrinkage. Shrinkage is usually small after three years of drying. After equilibrium has been reached under a given drying condition, a decrease in the relative humidity will result in more shrinkage. An increase in the relative humidity will result in expansion.[20]

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[18]Ibid. p. 240.

[19]Ibid. p. 244.

[20]Washa, G.W. Op. Cit. p. 121.

CHAPTER IV

LABORATORY INVESTIGATION PROGRAMME

SOILS INVESTIGATED

Three different soils were subjected to tests for shrinkage under different combinations of mixing, compaction and curing conditions. The soils selected for investigation were representative of soils used for soil-cement projects in Alberta. They were selected on a basis of grain size so that it could be determined to what extent the relative importance of the variables investigated were influenced by grading. A very fine sand and a very coarse sand were chosen to represent the extreme conditions; a medium fine sand was chosen to represent the intermediate condition. The cement which was used was type I normal Portland cement. Cement from the same batch was used with distilled water for all the specimens. The soils which were used in the investigation were as follows:[1]

(a) Hennig Pit Material:- This material came from a

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[1]Data sheets for grain size analysis, specific gravity and Standard Proctor compaction tests are contained in Appendix A. Some of the significant mechanical properties and a chemical analysis of the cement are contained in Appendix B.

borrow pit near Spruce Grove. ($NW^1/_4$ 20-52-27-4). It was used for soil-cement base course on Highway 16 from Station 730+00 to Station 830+00. It was a medium fine light brown sand (SP) with a uniformity coefficient of 2.3. The maximum Standard Proctor dry density as determined by the Department of Highways laboratory was 117.6 pounds per cubic foot and the optimum moisture content was 10.4 percent. The soil came from the B-horizon of the soil profile and had no apparent organic content. The soil was non-plastic. Table 3a shows the grain size distribution and the results of the design tests carried out by the Staff of the Department of Highways.

(b) Caywood Pit Material:- This material was from a borrow pit near Edmonton Beach Corner on Highway 16 ($SW^1/_4$ 7-53-1-5). It was originally intended for use on the Highway 16 soil-cement project from Station 1167+00 to the end of the project at Carvel Corner. When the pit was opened, however, it was found to contain insufficient usable material to finish the project. Consequently, a new pit was found with enough material to complete the project and the Caywood pit was abandoned. It was unfortunate that this occurred late in the summer, after the laboratory investigation was completed.

The Caywood material was a very fine greyish silty sand (ML) with a uniformity coefficient of six. The maximum Standard Proctor dry density, as determined by the Department

of Highways laboratory, was 107 pounds per cubic foot and the optimum moisture content was 14.5 percent. The soil came from the B-horizon of the soil profile and contained a trace of powdered coal. The soil was non-plastic. Table 3b shows the grain size distribution and the results of design tests carried out by the staff of the Department of Highways.

(c) Shepert Pit Material:- This material was from a borrow pit between Ashmont and St. Brides Corner on Highway 28 (NW$^1/_4$ 22-58-11-4). It was used for the soil-cement base course between Ashmont and St. Brides which was constructed during the summer of 1960. The material was a very coarse light brown uniform sand (SP) with a uniformity coefficient of 2.2. The maximum Standard Proctor dry density, as determined by the Department of Highways laboratory, was 121.5 pounds per cubic foot and the optimum moisture content was 9.5 percent. When the routine laboratory tests were carried out on this material, as a part of this study, results were obtained which differed appreciably from those of the Department of Highways laboratory. These are shown in Appendix A. Table 3c shows the grain size distribution and the results of design tests carried out by the staff of the Department of Highways. A maximum dry density of 115 pounds per cubic foot was used as a basis of the laboratory tests. A moisture content of eight percent was used for most of the specimens (except where the moisture content was

the variable under consideration) because specimens mixed at higher moisture contents crumbled when removed from the mold.

TABLE 3

Summary of Tests on Soil-Cement Mixtures
Carried out by Highways Testing Laboratory, Edmonton.

(a) Hennig Pit. Location - NW$^1/_4$ 20-52-27-4

Gradation Percent Passing	
No.4 Sieve - 100	Recommended Cement Content - 7% by wt.
No.8 Sieve - 100	
No.16 Sieve - 99.8	Laboratory Opt. Moisture - 10.4%
No.30 Sieve - 99	
No.50 Sieve - 84	Laboratory Max.Density - 117.6$^{lbs}/_{ft3}$
No.100 Sieve - 36	
No.200 Sieve - 5.8	

(b) Caywood Pit. Location - SW$^1/_4$ 7-53-1-5

Gradation Percent Passing	
No.4 Sieve- 100	Recommended Cement Content - 7% by wt.
No.8 Sieve- 99.9	
No.16 Sieve- 99.8	Laboratory Opt. Moisture - 14.5%
No.30 Sieve- 99.7	
No.50 Sieve- 99.6	Laboratory Max.Density - 107.0$^{lbs}/_{ft3}$
No.100 Sieve- 93	
No.200 Sieve- 52	

(c) Shepert Pit. Location - NW$^1/_4$ 22-58-11-4

Gradation Percent Passing	
No.4 Sieve- 89	Recommended Cement Content - 10%
No.8 Sieve- 71	
No.16 Sieve- 45	Laboratory Opt. Moisture - 9.4%
No.30 Sieve- 17	
No.50 Sieve- 3.6	Laboratory Max. Density - 121.5$^{lbs}/_{ft3}$
No.100 Sieve- 1.0	
No.200 Sieve- 0.4	

TESTING PROGRAMME

When the problem of shrinkage was first considered for this investigation, it was felt that, for a given soil, the most significant variables which should be investigated were: cement content, molding water content, degree of compaction and curing conditions. Accordingly, a laboratory investigation programme was drawn up to consider the possible combinations of these variables within a range of values which would represent conceivable field variations.

The first soil to be tested was that of the Hennig pit. This soil was subjected to six series of tests with each series representing different combinations of the four variables. The intent was to evaluate these results to determine the most significant variable combinations and derive from them a more efficient testing programme for the remaining two soils. As a result, the material from the Caywood pit and Shepert pit were each subjected to the three most significant series of tests as indicated by the first tests on the Hennig pit material.

The test series and variable combinations for each soil were as shown in tables 4a, 4b and 4c.

TABLE 4a

Summary of Test Series Carried Out On Material From Hennig Pit.

Test Series I	Compaction = 100% Standard Proctor Curing Condition - Soils Moist Room			
	Cement Content-Percent of Dry Wt.of Soil			
	5	7	9	11
Moisture content-percent of dry wt. of soil plus cement	8 10.4 12 14	8 10.4 12 14	8 10.4 12 14	8 10.4 12 14
Test Series II	Moisture Content = 10.4% Curing Condition-Soils Moist Room			
	Cement Content-Percent of Dry Wt.of Soil			
	5	7	9	11
Compaction-percentage of Standard Proctor	95 100 105 90	95 100 105 90	95 100 105 90	95 100 105 90
Test Series III	Moisture Content = 10.4% Compaction = 100% Standard Proctor			
	Cement Content-Percent of Dry Wt. of Soil			
	5	7	9	11
Curing Condition *	SMR OPEN CMR Sealed	SMR OPEN CMR Sealed	SMR OPEN CMR Sealed	SMR OPEN CMR Sealed

* SMR - Soils Moist Room - Relative Humidity = 70%
CMR - Concrete Moist Room - Relative Humidity = 100%
OPEN - Laboratory area - very low humidity
Sealed - Specimen Sealed in Polythene.

TABLE 4a - continued

Test Series IV	Compaction = 100% Standard Proctor Cement Content = 7%			
	Moisture Content - Percent			
	8	10.4	12	6
Curing Condition	Open SMR CMR Sealed	Open SMR CMR Sealed	Open SMR CMR Sealed	Open SMR CMR Sealed

Test Series V	Cement Content=7% Cured - Soils Moist Room			
	Moisture Content - Percent			
	8	10.4	12	6
Compaction percentage of Standard Proctor	95 100 105 90	95 100 105 90	95 100 105 90	95 100 105 90

Test Series VI	Cement Content = 7% Moisture Content = 10.4%			
	Compaction - Percent of Stan.Proctor			
	95	100	105	90
Curing Condition	SMR Open CMR Sealed	SMR Open CMR Sealed	SMR Open CMR Sealed	SMR Open CMR Sealed

TABLE 4b

Summary of Test Series Carried Out On Material from Caywood Pit.

Test Series I	Compaction = 100% Standard Proctor Curing Condition - Soils Moist Room			
	Cement Content-Percent of Dry Wt.of Soil			
	6	8	10	12
Moisture content-percent of Dry Wt. of Soil plus Cement	11 13 15 17	11 13 15 17	11 13 15 17	11 13 15 17

Test Series II	Moisture Content = 15% Curing Condition - Soils Moist Room			
	Cement Content-Percent of Dry Wt.of Soil			
	6	8	10	12
Compaction-Percentage of Standard Proctor	90 95 100 105	90 95 100 105	90 95 100 105	90 95 100 105

Test Series III	Moisture Content = 15% Compaction = 100% Standard Proctor			
	Cement Content-Percent of Dry Wt.of Soil			
	6	8	10	12
Curing Condition	Open SMR Sealed CMR	Open SMR Sealed CMR	Open SMR Sealed CMR	Open SMR Sealed CMR

TABLE 4c

Summary of Test Series Carried Out on Material from Shepert Pit

Test Series I	Compaction = 100% Standard Proctor Curing Condition - Soils Moist Room			
	Cement Content-Percent of Dry Wt.of Soil			
	6	8	10	12
Moisture Content - percent of Dry. Wt. of Soil plus cement	6 8 10 12	6 8 10 12	6 8 10 12	6 8 10 12
Test Series II	Moisture Content = 8% Curing Condition - Soils Moist Room			
	Cement Content-Percent of Dry Wt.of Soil			
	6	8	10	12
Compaction - percentage of Standard Proctor	95 100 105 110	95 100 105 110	95 100 105 110	95 100 105 110
Test Series III	Moisture Content = 8% Curing Condition - Soils Moist Room			
	Cement Content-Percent of Dry Wt.of Soil			
	6	8	10	12
Curing Condition	Open SMR CMR Sealed	Open SMR CMR Sealed	Open SMR CMR Sealed	Open SMR CMR Sealed

TESTING APPARATUS

Two essential pieces of apparatus required for this testing programme were suitable molds for forming the specimens and an accurate length comparator.

The molds were obtained by modifying the standard mold used for the preparation of cement-aggregate specimens for potential alkali reactivity tests.[2] Photo 1 shows the molds after they had been modified to include a collar and compacting head.[3]

Photo 2 shows the length comparator which consisted of a dial with direct reading to one-tenthousandth of an inch, permanently mounted on a cast steel frame. A steel bar with a rubber protected gripping area which was used as a standard reference for length is also shown in photo 2. Other special apparatus included a mechanical mixer which was used for mixing the soil, and a Black and Decker electric hammer which was used to compact the specimen. These units are shown in photos 3 and 4.

In addition to the special equipment, the standard laboratory equipment which was required included: a scale sensitive to 0.01 grams, spatulas, petri dishes, a dessicator

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[2]ASTM Designation: C 227 - 58T.

[3]Appendix C shows working drawings for the modified mold.

an assortment of pans and a drying oven.

A frame for mounting and loading the specimen to obtain the center point deflection under a single concentrated load was assembled as shown in Photo 5. Photo 6 shows three specimens representative of the three soil-cements which were investigated.

TESTING PROCEDURE

Data sheets for each set of specimens were prepared prior to mixing. These data sheets contained the proper amounts of each component of the mix to give the required design.[4] The soil, cement and water were mixed accordingly in the mechanical mixer. Immediately after mixing a representative sample of the soil-cement was taken for a moisture content determination.

The proper amount of soil-cement which was required to give the desired dry density when compacted to the mold dimensions was then placed in the mold by means of a small spatula. The compacting head was placed over the material in the mold and the electric hammer was used to compact the soil-cement to the required volume. After compaction the collar and reference point spacer screws were removed from the mold.

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[4]Sample Data sheets are contained in Appendix D.

It was then wrapped in polythene and placed in the concrete moist room at 100 per cent humidity for approximately twenty-four hours. Following this initial curing period, the specimens were removed from the mold and the length was immediately recorded. The sample was then stored in the specified curing condition which was one of the following:

(a) Soils Moist Room.- The soils moist room is maintained at a relative humidity of seventy per cent. The average temperature of this room during the testing programme was approximately twenty three degrees centigrade. Fluctuations from this temperature did not exceed plus or minus two centigrade degrees. This condition of curing was considered to be comparable to the field condition where a penetrating asphalt curing aid is used. Rapid curing and medium curing asphalts, when used as a curing aid in the field, penetrate the soil-cement up to one quarter of an inch and do not give a total seal.

The specimens designated for this condition of curing were left for a total of twenty-one days. During the first week of curing, the length of each specimen was recorded daily. Measurements were taken less frequently during the remainder of the curing period.

Following the three week curing period, the samples were placed in an oven at 105° C for twenty four hours. They were then removed and cooled in a dessicator before the final

length was recorded.

(b) Concrete Moist Room.- The concrete moist room is maintained at a relative humidity approaching 100 percent. The average temperature and fluctuations during the curing periods were of the same order as encountered in the soils moist room.

Specimens, which were designated for this curing condition, were left in this room for seven days. They were then removed and placed in the open laboratory area for the remainder of the twenty-one day curing period. This condition of curing was considered comparable to the field practice of keeping the soil-cement in a moist condition for a period of one week. Regular measurements, oven drying and final measurements were carried out as previously described.

(c) Open Laboratory Area.- The laboratory area has a very low relative humidity and is subjected to greater temperature fluctuations than either the concrete or the soils moist room. The average temperature during the testing period was twenty three degrees centigrade but fluctuations were plus or minus five centigrade degrees. This condition was selected as being comparable to the field condition where no curing aid is used. The specimens designated for this curing condition were left for a total of twenty-one days. Regular measurements, oven drying and final measurements were carried out as previously described.

(d) Sealed Condition.- Immediately after removal from the molds, specimens designated for this curing condition were wrapped in polythene and sealed with wax. This condition was selected as being comparable to a good non-penetrating skin-like field curing aid. In the field this condition is obtained by coating the dampened soil-cement with asphalt emulsion.

The specimens which were cured in this manner were left sealed for the entire twenty-one day period and were measured regularly as were the specimens subjected to the other curing conditions. Following the twenty-one day curing period, the seal was removed from the samples. They were then oven dried and measured in the same manner as the specimens subjected to the other curing conditions.

Following the final measurements, all specimens were deflected under center point loading to obtain a relative indication of strength. After this had been done, the specimens were broken into three pieces of approximately equal length for density determinations using the mercury immersion method.

DISCUSSION OF PROCEDURE

In the early stages of this investigation, the greatest problem was in the development of a mixing and compacting technique which would give a sound uniform

specimen. Another problem was that of finding a method to accurately measure total shrinkage.

Experiments were carried out to investigate several methods of compaction before the testing programme was started. These methods included: static loading and compaction of a specified quantity to a definite volume; a dropping weight compacting device with the material placed in two layers; the same dropping weight device but used on a compacting head to compact a specified quantity to a definite volume; a spring loaded tamper similar to the one used with the Harvard miniature compacting apparatus; a vibrating electric hammer used on a compacting head to compact a specified amount to a definite volume.

The last method was the one found most capable of giving a good uniform specimen of known density. It was, therefore, adopted as the compacting technique for the testing programme.

The sample mixing did not prove to be a problem. The time of mixing and the technique used with the mechanical mixer was arbitrarily adopted when it was found that a homogenous soil-cement mix was obtained.

The questionable aspect of the technique for measuring shrinkage was whether or not any shrinkage took place before the specimens were removed from the mold. To investigate this aspect, specimens were removed from the mold after they

had been in for six and one-half hours and twelve hours respectively. The time of set for the cement was six hours. The specimens were prepared from the Caywood pit material. Table 5a shows the change in length of each specimen for a thirty hour period following compaction. Specimens A and B were mixed in the same proportions as the Caywood specimen ID4. Specimens C and D correspond to the Caywood specimen IC4.

These results show that the specimens actually expand slightly during the twenty-four hour period following compaction. Shrinkage appears to begin somewhere between twenty-four and thirty hours after compaction. Compared to the ultimate shrinkage which the corresponding specimens underwent, this initial expansion was negligible.

This slight expansion could be due to the dilation of the cement paste during setting. Table 5b shows the dilation of a specimen of paste which was determined experimentally by H.H. Steinour and reported by T.C. Powers, both of the Portland Cement Association.[1]

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[1]Powers T.C. "Some Physical Aspects of the Hydration of Portland Cement." Journal of the Research and Development Laboratories, Portland Cement Association. Vol. 3, No. 1, Jan. 1961. p. 51.

TABLE 5a

Unit change in length of Caywood soil-cement specimens for a 30 hour period following compaction.

Specimen	A	B	C	D
Cement Content %	12	12	10	10
Moisture Content %	17	17	15	15
Dry Density ^{lbs}/cu.ft.	107	107	107	107
Time in mold - hrs.	6.5	12	6.5	12
Age After Compaction	Change in length - millionths *			
6.5 Hrs.	0	-	0	-
8	0	-	+20	-
9	+10	-	+20	-
12	-	0	-	0
15	-	+10	-	+20
18	+30	-	+30	-
21	+30	-	+20	-
24	+20	-10	+20	+10
27	-10	-30	0	0
30	-50	-50	-30	-10

* (+) - Expansion (-) - Shrinkage

TABLE 5b

Dilation of cement paste during setting as reported by T.C. Powers, Portland Cement Association.

Age at end of bleeding period - 1 hr. 12 min. Age at beginning of expansion - 1 hr. 30 min. (Cement No. 15754)		
Age Interval Hr.	Rate of dilation %/Hr.	Total dilation %
0-1.5	0	0
1.5-2.5	0.10	0.10
2.5-3.5	0.04	0.14
3.5-4.5	0.04	0.18
4.5-5.5	0.02	0.20
5.5-6.5	0.02	0.22*
6.5-23.5	0.01	0.38

*Time of final set.

It was found that if specimens were removed before having at least eighteen hours in the mold, over one half of them were broken upon removal. Although it was found that most of the specimens could be safely removed from the molds after eighteen hours, a period of twenty to twenty-four hours was used since it fitted into a regular laboratory routine.

A difficulty in determining the shrinkage properties of the specimens was the selection of a common datum for comparison. In a laboratory investigation of shrinkage of compacted soils carried out in India, the comparison of volumetric shrinkage of soils treated with different amounts of cement was based on the shrinkage which occurred after seven days curing and then drying in an oven.[6]

The oven drying of soil-cement specimens can not be considered as representative of any condition encountered in the field. The most ideal condition for this investigation would have been to allow the specimens to arrive at equilibrium with respect to shrinkage in an environment which was representative of the field conditions.

The conditions of curing in the field undergo many variations, particularly due to changes in the climate and

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[6]Mehra and Uppal, Op. Cit. p. 323.

changes in the subgrade moisture conditions. The environment of the soil-cement in the field also undergoes a change when the road mix or bituminous surface course is applied. In Alberta, a minimum curing period of three weeks is specified before the road mix is applied. The best laboratory representation of this condition would probably be to seal all of the specimens after three weeks of curing and then allow them to come to equilibrium in their new environment. Even then, this could not be considered completely representative of the field conditions, since soil-cement in the field is subjected to changes in climate and subgrade moisture conditions. There is also a time element, which could exceed several months, for the soil-cement to reach equilibrium with respect to shrinkage.

In the light of these considerations, it was felt that the best approach to the problem was to allow the specimens to cure for three weeks, under a controlled curing condition, and then place them in a common environment with which they would quickly come to equilibrium. This would provide a common basis for an evaluation of the results. Oven drying the specimens appeared to be the only method of providing this common basis without becoming involved in a time element of unknown duration.

It is possible that if the specimens were placed in some other environment, the trends of shrinkage may have been

different than those obtained by using the oven drying technique. The choice of the best laboratory environment to represent field conditions would be largely a matter of opinion. Almost any condition of storage in the laboratory would be open to some objections.

It was felt by the writer that the oven drying technique would not give a true indication of the magnitude of the ultimate shrinkage of the soil-cement which would occur under field conditions, but that it would give a true indication of the relative importance of the variable factors investigated, as they affected shrinkage. This was based on the presumption that, after a three week curing period, a change in the environment of the soil-cement will affect the total shrinkage which it might undergo but it should not affect the other significant factors which influence shrinkage.

Therefore, for the remainder of this report, unless otherwise specified, any reference to lineal shrinkage of the laboratory specimens, is the total shrinkage after three weeks curing and subsequent oven drying.

The apparatus, which was used to obtain the flexural strength of the specimens was a bit cumbersome. However, since the specimens were so sensitive and fragile, it was felt that a further refinement of the apparatus would not significantly improve the results of this test. This test was not considered to be an integral part of this

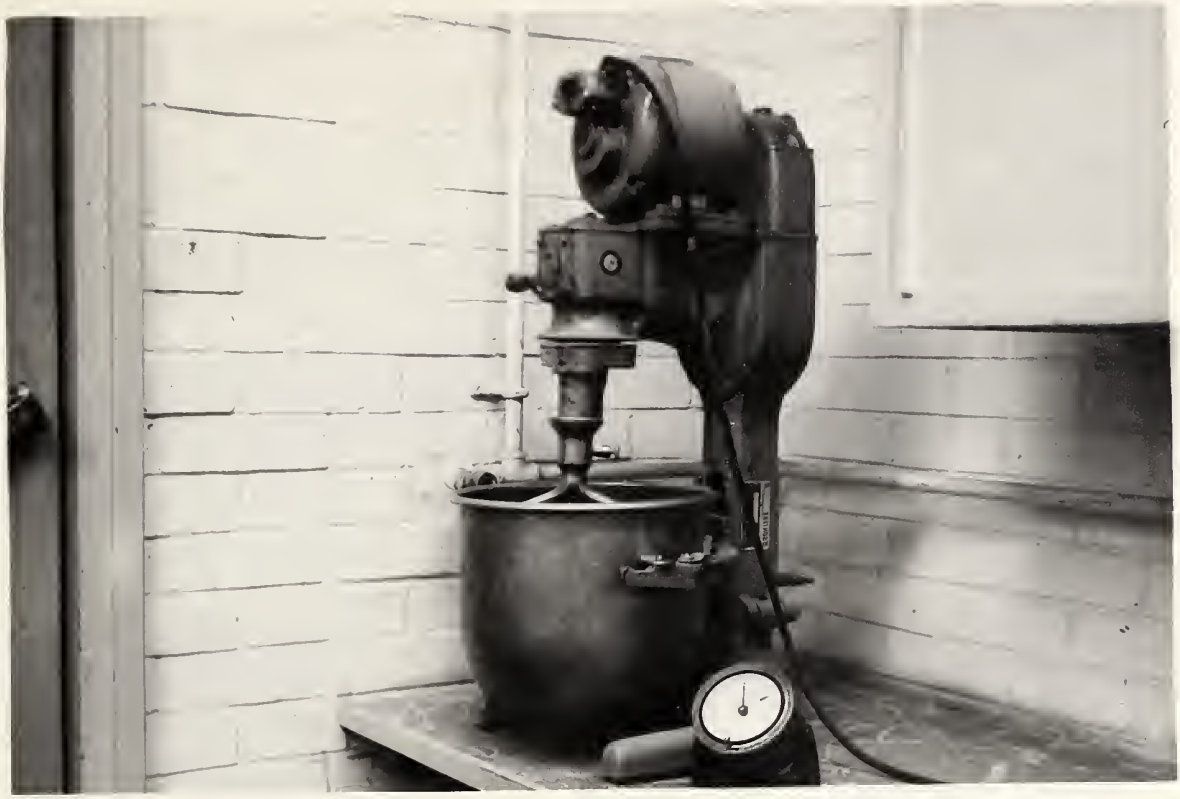
investigation but was carried out mainly to give a relative indication of strength of the soil-cement specimens.

PHOTOGRAPH 1

Specimen Mold, Compacting Head, Collar, and Collar Ties.

PHOTOGRAPH 2

Length Comparator with Specimen and Steel Bar for Standard Length Reference.

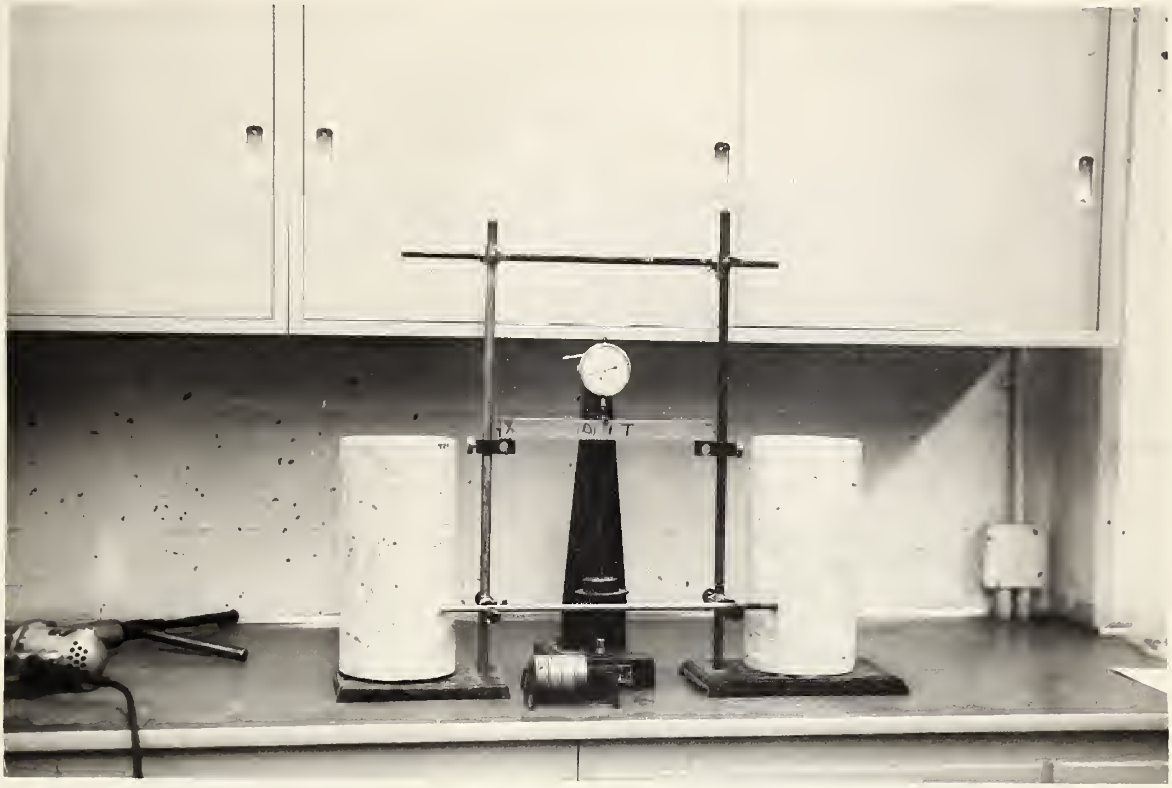


PHOTOGRAPH 3

Fifteen Quart Mechanical Soil Mixer.

PHOTOGRAPH 4

Compacting Specimen With Electric Hammer.



PHOTOGRAPH 5

Frame For Testing Specimen For Flexural Strength.

PHOTOGRAPH 6

Typical Specimens.

CHAPTER V

RESULTS OF THE LABORATORY INVESTIGATION

SOIL-CEMENT MADE FROM THE HENNIG PIT MATERIAL

A summary of the results of the laboratory investigation of the material from the Hennig pit is contained in tables 6 to 11. In all cases the value of the lineal shrinkage is the total shrinkage in millionths, after the specimens had been oven dried. These results are produced graphically on plates 1 to 8.

Plate 1 shows the relationship between lineal shrinkage and cement content for samples mixed at different moisture contents. The values of the moisture contents as shown on the plates are the values corresponding to the mix design. The values of moisture content, which were determined after the sample was mixed, are shown in table 6. In practically all cases the moisture contents were within plus or minus 0.5 percent of the design value.

These results show that a fairly straight line relationship exists between lineal shrinkage and cement content. For the mixes investigated an increase in cement content resulted in an appreciable increase in shrinkage.

Plate 2 is derived from the same test series as plate 1. It shows the relationship between lineal shrinkage and

moisture content for samples prepared at different cement contents. The values of moisture content which are plotted are those shown in table 6. It can be seen that the relationship between shrinkage and moisture content approximates a straight line. With an increase in moisture content, there is a proportional increase in lineal shrinkage.

Plate 3 shows the relationship between lineal shrinkage and compacted dry density. It can be seen that for a low cement content of five percent, the dry density of the material appears to have very little effect on shrinkage. However, as the cement content is increased, the lineal shrinkage decreases with increased density. The relationship between lineal shrinkage and dry density approximates a straight line for all cement contents investigated.

Plate 4 shows the relationship between lineal shrinkage and cement content for specimens which were cured under different conditions. The results of this test series are not very consistent. The specimens which were sealed for the entire curing period were probably under the best curing condition with respect to development of strength. At low cement contents however, these specimens shrank more than specimens cured in the open laboratory area and more than those cured in the soils moist room. At cement contents above seven percent, the sealed specimens shrank less than all

other specimens at corresponding cement contents. For all cement contents investigated, the greatest amount of shrinkage occurred in the specimens which were cured at one hundred percent humidity for one week.

Plate 5 shows the relationship between lineal shrinkage and moisture content for specimens cured under different conditions. This test series does not add much to what is already known from the first three series of tests. Lineal shrinkage increases with moisture content and is affected to a lesser degree by curing conditions. Generally, the samples which were sealed shrank less than the samples which were subjected to other conditions of curing.

Plate 6 shows the relationship between shrinkage and dry density for samples prepared with different initial moisture contents. Once again there is a fairly straight line relationship between lineal shrinkage and dry density. The initial moisture content has some effect on the shrinkage, particularly at higher densities.

Plate 7 shows the relationship between lineal shrinkage and dry density for specimens cured under different conditions. The trend is again a straight line relationship between shrinkage and density, with a slight scatter of points due to the various conditions of curing. The different conditions of curing appear to be more significant at higher dry densities.

Plate 8 shows the relationship between shrinkage and time for similar specimens which were subjected to different curing conditions. After twenty-one days curing, the specimens were oven dried. The amount of shrinkage, which took place due to the oven drying appears to be a function of the moisture content of the specimen at the time it was placed in the oven. The sealed specimens had an average moisture content before drying of 7.4 percent. The specimens cured in the concrete moist room had an average moisture content of 1.25 percent. Those cured in the open air and soils moist room had moisture contents before drying of 1.4 and 1.5 percent respectively.

The shrinkage which took place in the sealed specimens before they were place in the oven appears to be what is referred to as autogenous shrinkage in concrete technology.

The specimens which were cured under room conditions (open) appear to have reached equilibrium, with respect to shrinkage, after one day. The specimens cured in the soils moist room reached equilibrium after about seven days. The specimens which were cured in the concrete moist room underwent autogenous shrinkage until they were placed under room conditions. They then shrank rapidly for two days until they came to equilibrium in their new environment.

The final shrinkage after oven drying of the sealed

specimens was less than that of specimens cured under the other three conditions.

THE RELATIVE IMPORTANCE OF THE FACTORS AFFECTING SHRINKAGE OF THE HENNIG PIT SOIL-CEMENT

In the usual plant mix production of soil-cement there will be variations in the mix proportioning and in the compacted dry densities. The range of values selected for investigation in the laboratory are representative of the normal variations which occur in production. Examinations of field control data show that cement and moisture content are usually maintained within plus or minus two percent of the desired values. The specified minimum density for most projects is ninety-seven percent of Standard Proctor density; however, it is not uncommon to find densities as low as ninety-five percent of Standard Proctor. Similarly values as high as 105 percent of Standard Proctor density are not uncommon.

It has also been noted that the nature of the seal coat applied in the field varies considerably. In some cases a penetrating curing aid is used. In other places a non-penetrating asphaltic membrane is applied. Occasionally the soil-cement is kept moist by spraying with water for a specified curing period, before the seal coat is applied.

On a basis of the normal variations that can be expected in the field, the four variables investigated can be arranged in their relative order of importance as they affect shrinkage as follows:

(1) Cement content.

(2) Compacted dry density.

(3) Initial moisture content.

(4) Curing conditions.

TABLE 6

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

HENNIG PIT

TEST SERIES	CEMENT %	WATER %	DENSITY LBS/FT^3	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI× 10^{-6}	REMARKS
IA1(a)	5	76	118	SMR	820		-	
(b)	5	7.6	117	SMR	810	815	.45	
IA2(a)	5	10.5	116.7	SMR	970		.36	
(b)	5	10.5	117.3	SMR	1080	1025	-	
IA3(a)	5	11.8	118.1	SMR	1110		.36	
(b)	5	11.8	117.3	SMR	1080	1095	.28	
IA4(a)	-	-	-	-	-	-	-	broke
(b)	5	13.7	116.3	SMR	1350	1350	-	
IB1(a)	7	7.9	118.4	SMR	1200		-	
(b)	7	7.9	-	SMR	1200	1200	.67	
IB2(a)	7	10.3	118.7	SMR	1420		-	
(b)	7	10.3	119	SMR	1470	1445	.47	
IB3(a)	7	11.7	118.1	SMR	1620		-	
(b)	7	11.7	118.2	SMR	1500	1560	.47	
IB4(a)	7	14	117	SMR	1610		.25	
(b)	7	14	115.6	SMR	1650	1630	.-	
IC1(a)	9	7.5	118.6	SMR	1510		-	
(b)	9	7.5	119.7	SMR	1500	1505	.28	
IC2(a)	9	10.3	118.1	SMR	1670		-	
(b)	9	10.3	118.2	SMR	1690	1680	-	
IC3(a)	9	11.6	117.6	SMR	1700		.55	
(b(	-	-	-	-	-	1700	-	broke
IC4(a)	9	15.3	115.9	SMR	1840		-	
(b)	9	15.3		SMR	2000	1920	-	
ID1(a)	11	7.8	120.6	SMR	1700		.67	
(b)	11	7.8	120.4	SMR	1780	1740	-	
ID2(a)	11	10.1	121	SMR	1860		1.42	
b)	11	10.1	120.9	SMR	1960	1910	-	
ID3(a)	11	12.1	120.5	SMR	1940		.45	
(b)	11	12.1	120.1	SMR	2010	1975	1.42	
ID4(a)	11	-	-	-	-		-	broke
(b)	11	13.4	119	SMR	2180	2180	-	

TABLE 7

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

HENNIG PIT

TEST SERIES	CEMENT %	WATER %	DENSITY LBS/FT^3	CURING CONDITION	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI x 10^{-6}	REMARKS
IIA1(a)	5	11.5	114.2	SMR	960		.30	
(b)	5	11.5	114.2	SMR	990	975	.38	
2(a)	5	10.5	116.7	SMR	970		.36	IA2
(b)	5	10.5	117.3	SMR	1080	1025	-	"
3(a)	5	9.8	120.2	SMR	1070		.45	
(b)	5	9.8	119.9	SMR	940	1005	.57	
4(a)	5	10.4	110.5	SMR	990	990	-	
(b)	-	-	-	-	-	-	-	broke
IIB1(a)	7	10.0	113.7	SMR	1730		.35	
(b)	7	10.0	113.4	SMR	1660	1695	.45	
2(a)	7	10.3	118.7	SMR	1420		-	IB2
(b)	7	10.3	119	SMR	1470	1445	.47	"
3(a)	7	10.1	121.5	SMR	1240		.64	
(b)	7	10.1	120.9	SMR	1400	1340	.60	
4(a)	7	10.2	109.1	SMR	1860		-	
(b)	7	10.2	109.0	SMR	1700	1780	-	
IIC1(a)	9	10.0	114.3	SMR	1790		.30	
(b)	9	10.0	114.2	SMR	1710	1750	.71	
2(a)	9	10.3	118.1	SMR	1570		-	IC2
(b)	9	10.3	118.2	SMR	1690	1580	-	"
3(a)	9	10.0	122.4	SMR	1290		-	
(b)	9	10.0	122.1	SMR	1530	1410	-	
4(a)	9	10.1	110	SMR	1800		.58	
(b)	9	10.1	111.5	SMR	1820	1810	.39	
IID1(a)	11	10.4	115.8	SMR	1860		.51	
(b)	11	10.4	115.3	SMR	1830	1845	.49	
2(a)	11	9.7	121	SMR	1860		-	ID2
(b)	11	9.7	120.9	SMR	1960	1910	-	"
3(a)	11	10.4	123.9	SMR	1400		.64	
(b)	11	10.4	123.5	SMR	1790	1595	[illegible]	
4(a)	11	10.6	108.0	SMR	2040	2040	.38	
(b)	11	-	-	-	-		-	broke

TABLE 8

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

HENNIG PIT

TEST SERIES	CEMENT %	WATER %	DENSITY LBS/FT^3	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI × 10^{-6}	REMARKS
IIIA1(a)	5	10.4	116.4	Open	920		-	
b	5	10.4		Open	800	860	-	
2a	5	10.5	116.7	SMR	970		-	IA2
b	5	10.5	117.3	SMR	1080	1020	-	IA2
3a	5	10.5	117.1	CMR	1150		.26	
b	5	10.5	116.9	CMR	1100	1125	.27	
4a	5	10.3	116.4	Sealed	1000		.26	
b	5	10.3		Sealed	1300	1150	.24	
IIIB1a	7	10.2	117.7	Open	1330		.24	
b	7	10.2	117.4	Open	1150	1240	-	
2a	7	10.3	118.7	SMR	1420		.47	IB2
b	7	10.3	119	SMR	1470	1445	-	"
3a	7	10.1	117.4	CMR	1550		.55	
b	7	10.1	117.5	CMR	1730	1640	.40	
4a	7	9.7	117.8	Sealed	1280		.38	
b	7	9.7	118	Sealed	1200	1240	.50	
IIIC1a	9	10.4	120.5	Open	1500		.34	
b	9	10.4	118	Open	1440	1470	-	
2a	9	10.3	118.1	SMR	1810		-	IC2
b	9	10.3	118.2	SMR	1710	1760	-	"
3a	9	10.1	121	CMR	1850		.53	
b	9	10.1	120.8	CMR	1680	1760	.55	
4a	9	10.7	119.4	Sealed	1450		-	
b	9	10.7	120.1	Sealed	1440	1445	-	
IIID1a	11	10.2	120.5	Open	1900		.40	
b	11	10.2	121	Open	1820	1860	.28	
2a	11	9.7	121	SMR	1860		1.42	
b	11	9.7	120.9	SMR	1960	1910	-	
3a	11	10.4	121	CMR	2070	2070	.60	
b	-	-	-	-	-	-	-	broke
4a	11	10.0	121.1	Sealed	1420		.35	
b	11	10.0	120.2	Sealed	1380	1400	.94	

TABLE 9

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

HENNIG PIT

TEST SERIES	CEMENT %	WATER %	DENSITY LBS/FT	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI × 10^{-6}	REMARKS
IV A1a	7	8.0	117.8	Open	1190		.26	
b	7	8.0	118.0	Open	1100	1145	.28	
2a	7	7.9	118.4	SMR	1350		-	
b	7	7.9	118.0	SMR	1200	1275	-	
3a	7	8.0	119.0	CMR	1480		.53	
b	7	8.0	119.4	CMR	1290	1358	.55	
4a	7	8.3	117.8	Sealed	1350		.76	
b	7	8.3	118.7	Sealed	1280	1315	.87	
IV B1a	7	10.2	117.7	Open	1350		.24	
b	7	10.2	117.4	Open	1150	1240	-	
2a	7	10.3	118.7	SMR	1420		.47	
b	7	10.3	119.0	SMR	1470	1440	-	
3a	7	10.1	117.4	CMR	1550		.55	
b	7	10.1	117.5	CMR	1730	1640	.40	
4a	7	9.7	117.8	Sealed	1200		.38	
b	7	9.7	118.0	Sealed	1280	1240	.50	
IVC1a	7	11.9	117.3	Open	1370	1370	.1[illegible]	
b	-	-	-	-	-	-	-	Broke
2a	7	11.7	118.1	SMR	1620		-	
b	7	11.7	118.2	SMR	1500	1560	.47	
3a	7	12.0	119.0	CMR	1520		.39	
b	7	12.0	119.0	CMR	1490	1505	.32	
4a	7	11.6	119.5	Sealed	1220		-	
b	7	11.6	118.4	Sealed	1380	1300	-	
IVD1a	7	6.3	117.4	Open	900		.87	
b	7	6.3	117.0	Open	820	860	.67	
2a	7	6.1	119.1	SMR	1220		-	
b	7	6.1	118.6	SMR	1270	1248	-	
3a	7	6.4	117.6	CMR	1180		-	
b	7	6.4	117.9	CMR	1000	1090	-	
4a	7	6.1	116.5	Sealed	870		-	
b	7	6.1	118.5	Sealed	920	895	-	

TABLE 10

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

HENNIG PIT

TEST SERIES	CEMENT %	WATER %	DENSITY LBS/FT^3	CURING CONDITION	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI x 10^{-6}	REMARKS
VA 1a	7	7.7	114.2	SMR	1650		-	
b	7	7.7	114	SMR	1690	1670	-	
2a	7	7.9	118.4	SMR	1420		-	
b	7	7.9	-	SMR	1470	1445	-	
3a	7	8.0	122	SMR	1390		-	
b	7	8.0	121.9	SMR	1350	1370	-	
4a	7	8.0	110.2	SMR	1790		-	
b	7	8.0	110.2	SMR	1780	1785	-	
VB 1a	7	10.0	113.7	SMR	1730		.35	
b	7	10.0	113.4	SMR	1660	1695	.45	
2a	7	10.3	118.7	SMR	1420		-	
b	7	10.3	119	SMR	1470	1440	.47	
3a	7	10.1	121.5	SMR	1240		.64	
b	7	10.1	120.9	SMR	1440	1340	.60	
4a	7	10.2	109.1	SMR	1860		-	
b	7	10.2	109	SMR	1700	1780	-	
VC 1a	7	12.0	115.3	SMR	1620		-	
b	7	12.0	115.0	SMR	1590	1605	-	
2a	7	11.7	118.1	SMR	1620		-	
b	7	11.7	118.2	SMR	1500	1560	-	
3a	7	11.9	121.1	SMR	1490		-	
b	7	11.9	121.5	SMR	1390	1450	-	
4a	7	11.3	110	SMR	1810	1810	-	
b	-	-	-	-	-	-	-	broke
VD 1a	7	6.4	113.6	SMR	1640		.87	
b	7	6.4	114.0	SMR	1640	1640	.67	
2a	7	6.1	119.1	SMR	1220		-	
b	7	6.1	118.6	SMR	1270	1245	-	
3a	-	-	-	-	-	-	-	broke
b	7	6.3	119.7	SMR	1260	1260	.81	
4a	7	6.3	109.5	SMR	1720		.38	
b	7	6.3	109.5	[illegible]	1690	1705	.42	

TABLE II

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

HENNIG PIT

TEST SERIES	CEMENT %	WATER %	DENSITY LBS/FT^3	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI$\times 10^{-6}$	REMARKS
VIA 1a	7	10.0	113.7	SMR	1730		.35	
b	7	10.0	113.4	SMR	1660	1695	.45	
2a	7	10.4	112.3	Open	1580		.16	
b	7	10.4	112.3	Open	1510	1545	-	
3a	7	10.6	113	CMR	1520		.28	
b	7	10.6	113	CMR	1470	1495	.23	
4a	7	10.7	112.4	Sealed	1740		.32	
b	7	10.7	114.3	Sealed	1600	1670	.40	
VI B1a	7	10.2	117.7	Open	1330		.24	
b	7	10.2	117.4	Open	1150	1240	-	
2a	7	10.3	118.7	SMR	1420		.47	
b	7	10.3	119	SMR	1470	1440	-	
3a	7	10.1	117.4	CMR	1550		.55	
b	7	10.1	117.5	CMR	1750	1640	.40	
4a	7	9.7	117.8	Sealed	1200		.38	
b	7	9.7	118	Sealed	1280	1240	.50	
VIC 1a	7	10.1	121.5	SMR	1240		.64	
b	7	10.1	120.9	SMR	1440	1340	.60	
2a	7	11.2	120.9	Open	1340		-	
b	7	11.2	120.4	Open	1320	1310	.29	
3a	7	10.6	120.5	CMR	1720		.43	
b	7	10.6	120.2	CMR	1570	1645	.55	
4a	7	10.4	121	Sealed	1450		1.00	
b	7	10.4	121.1	Sealed	1340	1375	.58	
VID 1a	7	10.2	109.1	SMR	1800		-	
b	7	10.2	109	SMR	1700	1780	-	
2a	-	-	-	-	-	-	-	broke
b	7	10.5	109.5	Open	1600	1600	-	
3a	7	10.4	108.5	CMR	1760	1760	-	
b	-	-	-	-	-	-	-	broke
4a	7	10.4	109.3	Sealed	1550	1500	.55	
b	-	-	-	-	-	-	-	broke

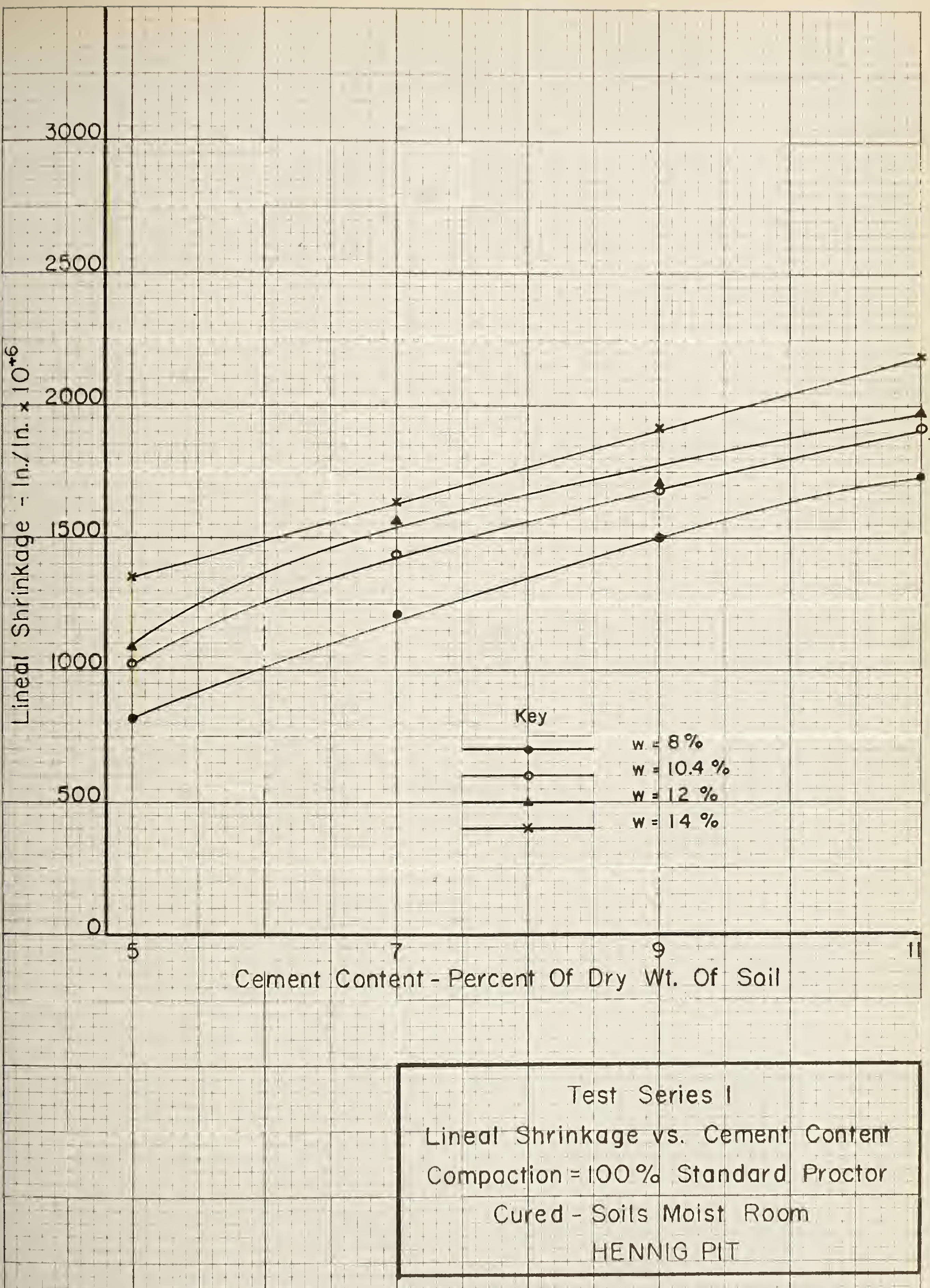
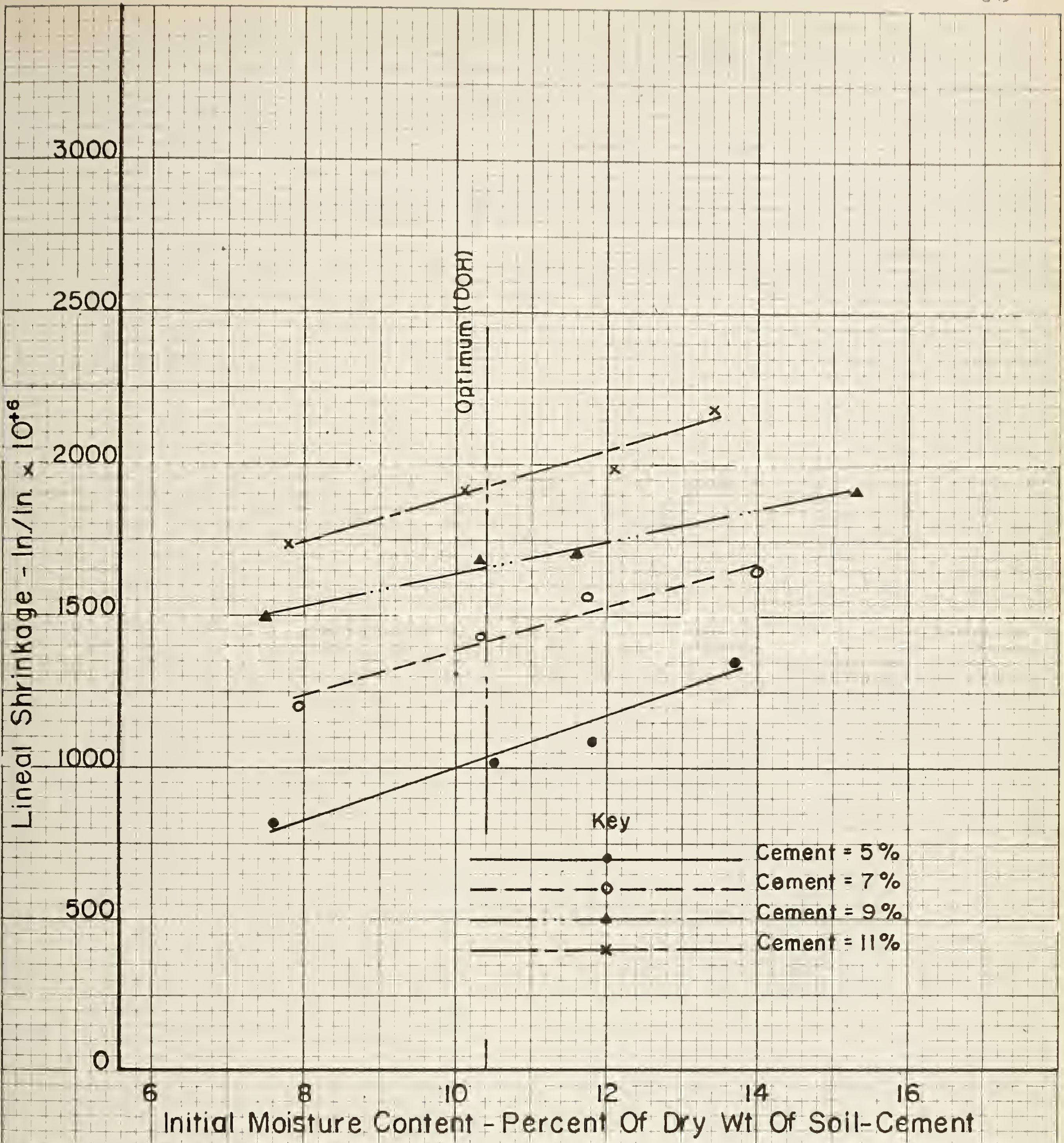
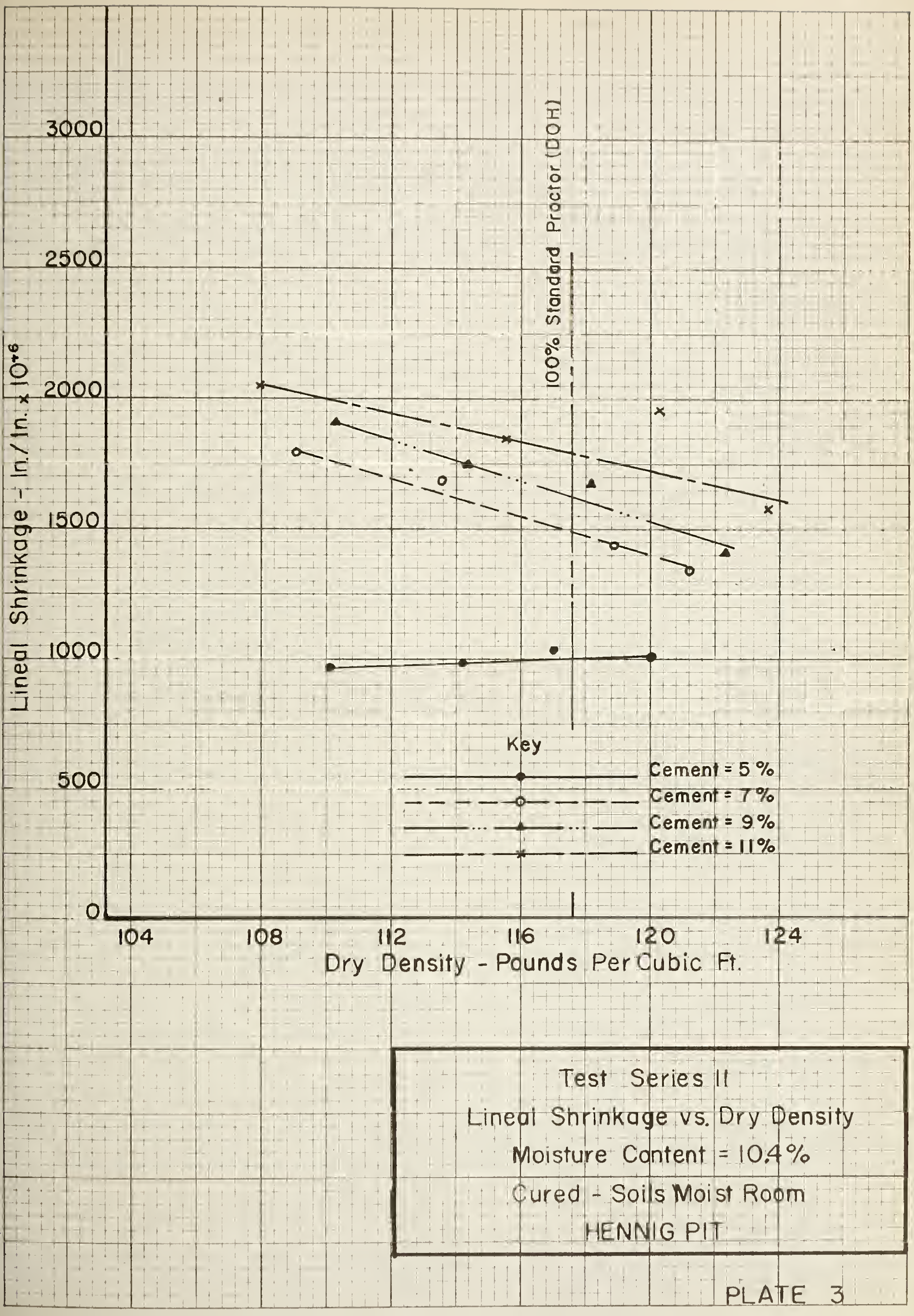

Lineal Shrinkage - In./In. x 10+6
0
500
1000
1500
2000
2500
3000
5
7
9
11
Cement Content - Percent Of Dry Wt. Of Soil
Key
w = 8 %
w = 10.4 %
w = 12 %
w = 14 %
Test Series I
Lineal Shrinkage vs. Cement Content
Compaction = 100 % Standard Proctor
Cured - Soils Moist Room
HENNIG PIT

PLATE I



Test Series I
Lineal Shrinkage vs Moisture Content
Compaction = 100% Standard Proctor
Cured - Soils Moist Room
HENNIG PIT

PLATE 2


3000
2500
2000
1500
1000
500
0
Lineal Shrinkage - In./In. x 10+6
100% Standard Proctor (DOH)
104
108
112
116
120
124
Dry Density - Pounds Per Cubic Ft.
Key
Cement = 5 %
Cement = 7 %
Cement = 9 %
Cement = 11%
Test Series II
Lineal Shrinkage vs. Dry Density
Moisture Content = 10.4%
Cured - Soils Moist Room
HENNIG PIT
PLATE 3

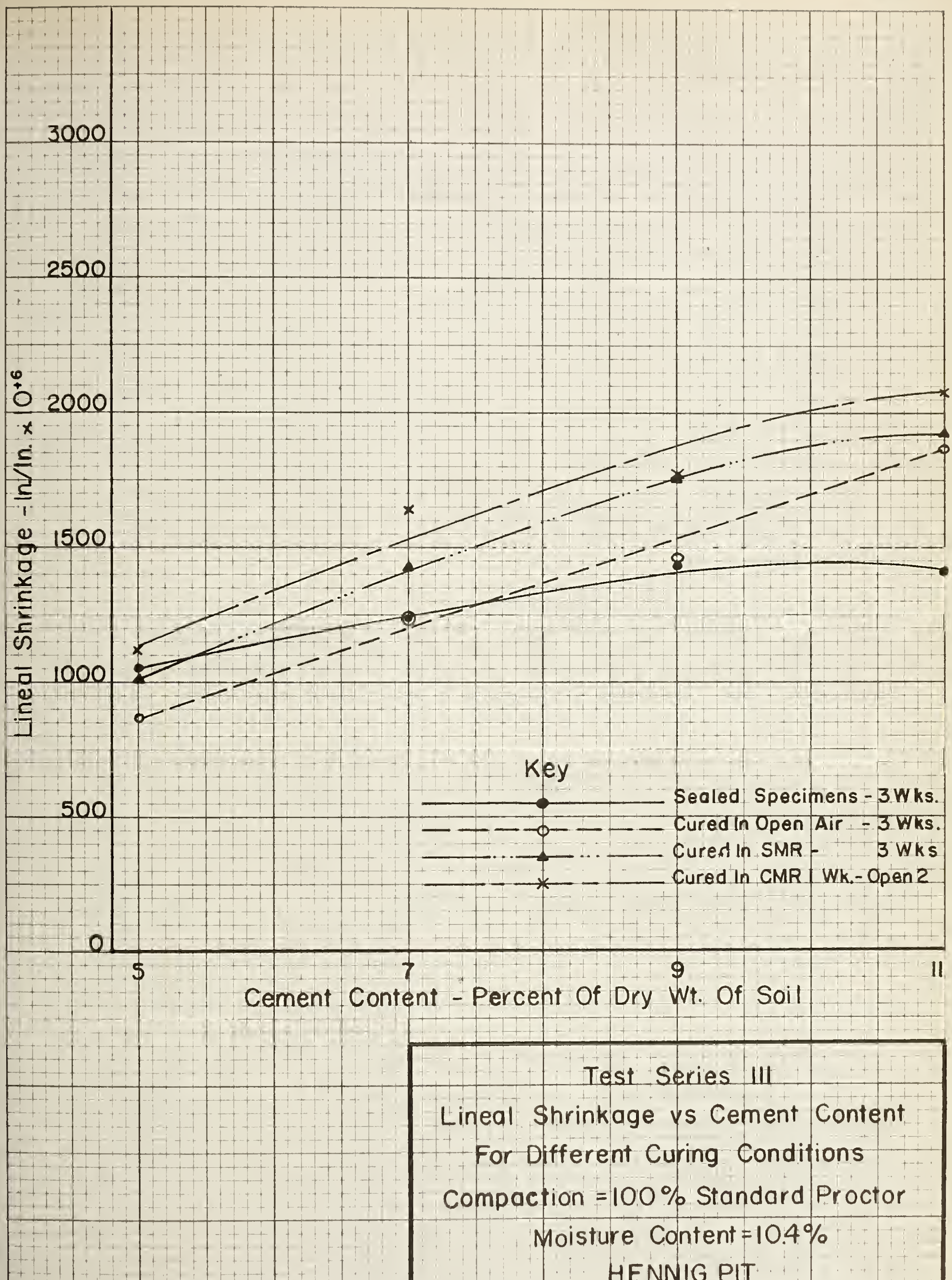
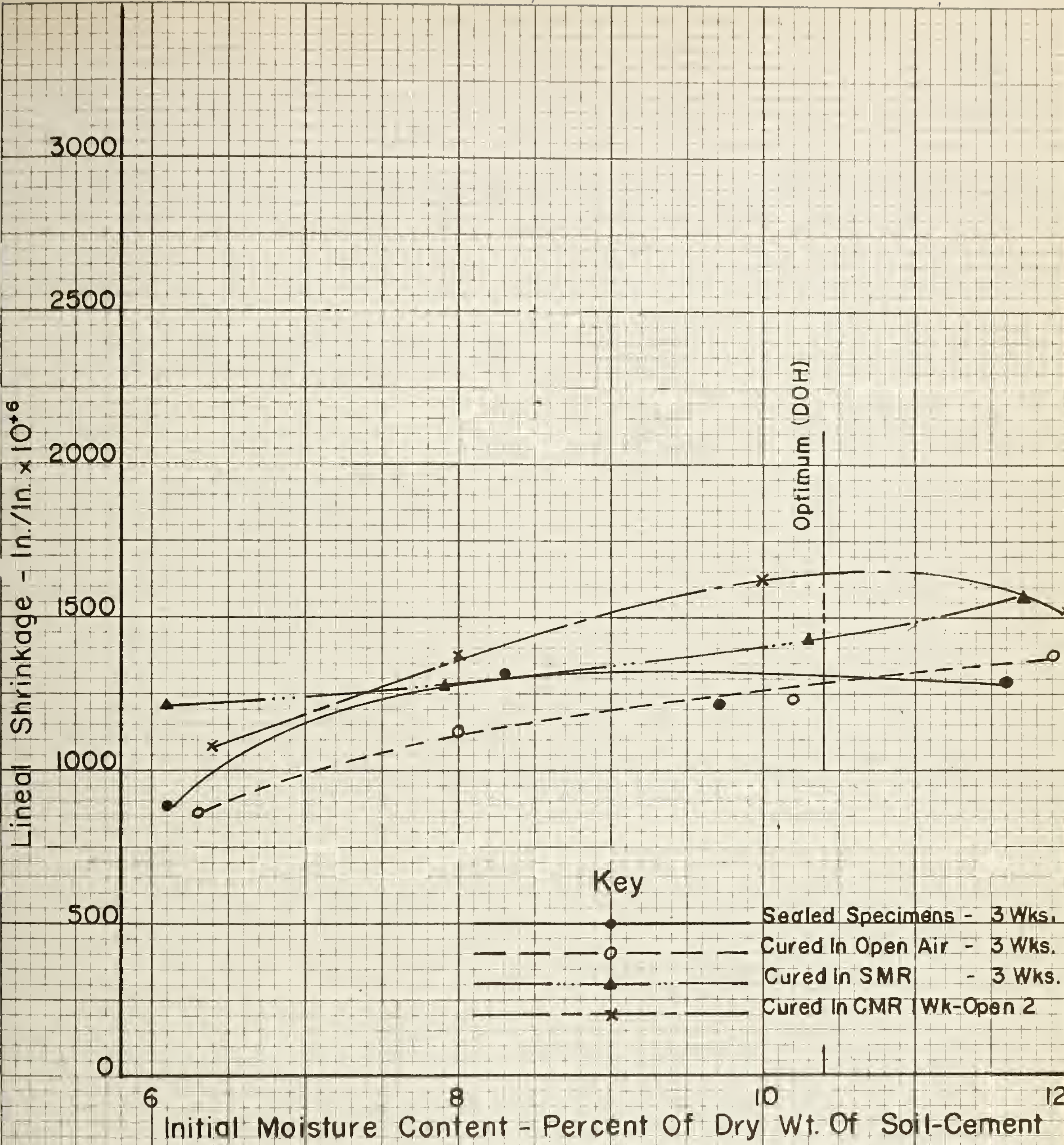
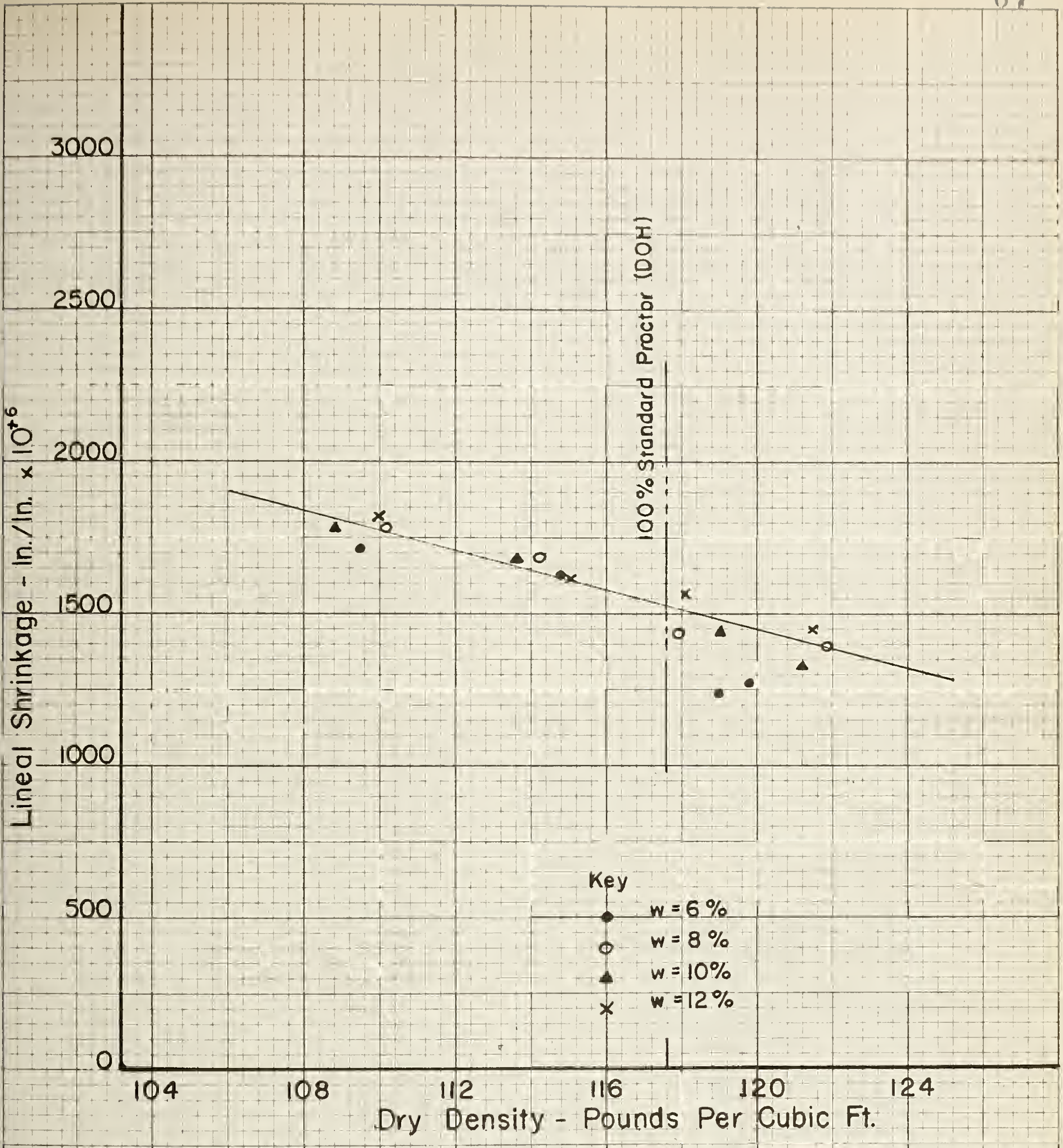

3000
2500
2000
1500
1000
500
0
Lineal Shrinkage - In/In. x 10+6
5
7
9
11
Cement Content - Percent Of Dry Wt. Of Soil
Key
Sealed Specimens - 3 Wks.
Cured In Open Air - 3 Wks.
Cured In SMR - 3 Wks
Cured In CMR 1 Wk.- Open 2
Test Series III
Lineal Shrinkage vs Cement Content
For Different Curing Conditions
Compaction = 100 % Standard Proctor
Moisture Content = 10.4 %
HENNIG PIT

PLATE 4



Test Series IV
Lineal Shrinkage vs. Moisture Content
For Different Curing Conditions
Compaction = 100 % Standard Proctor
Cement Content = 7 %
HENNIG PIT

PLATE 5



Test Series V

Lineal Shrinkage vs Dry Density

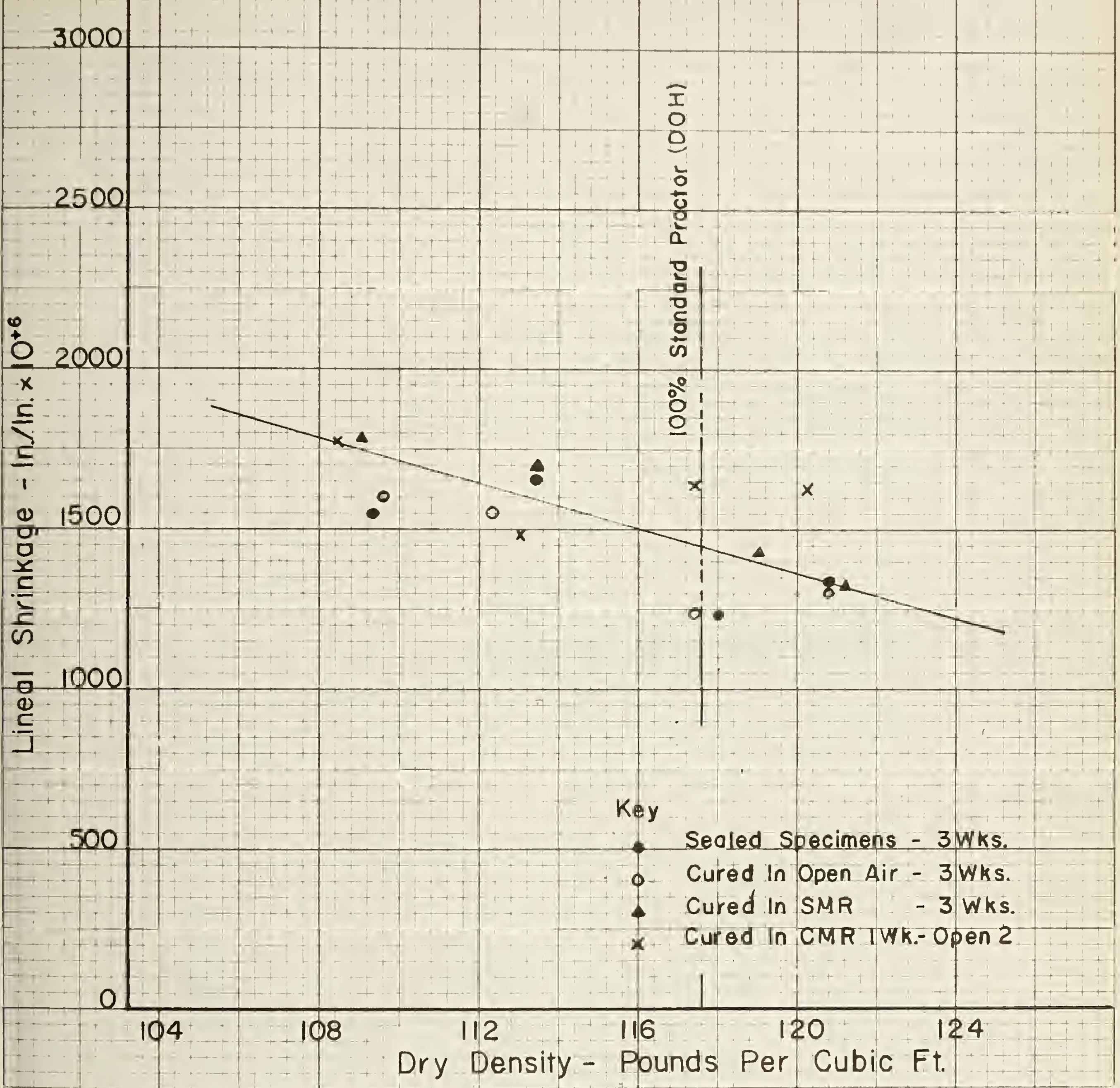
For Different Moisture Contents

Cement Content = 7%

Cured Soils Moist Room

HENNIG PIT

PLATE 6



Test Series VI

Lineal Shrinkage vs. Dry Density

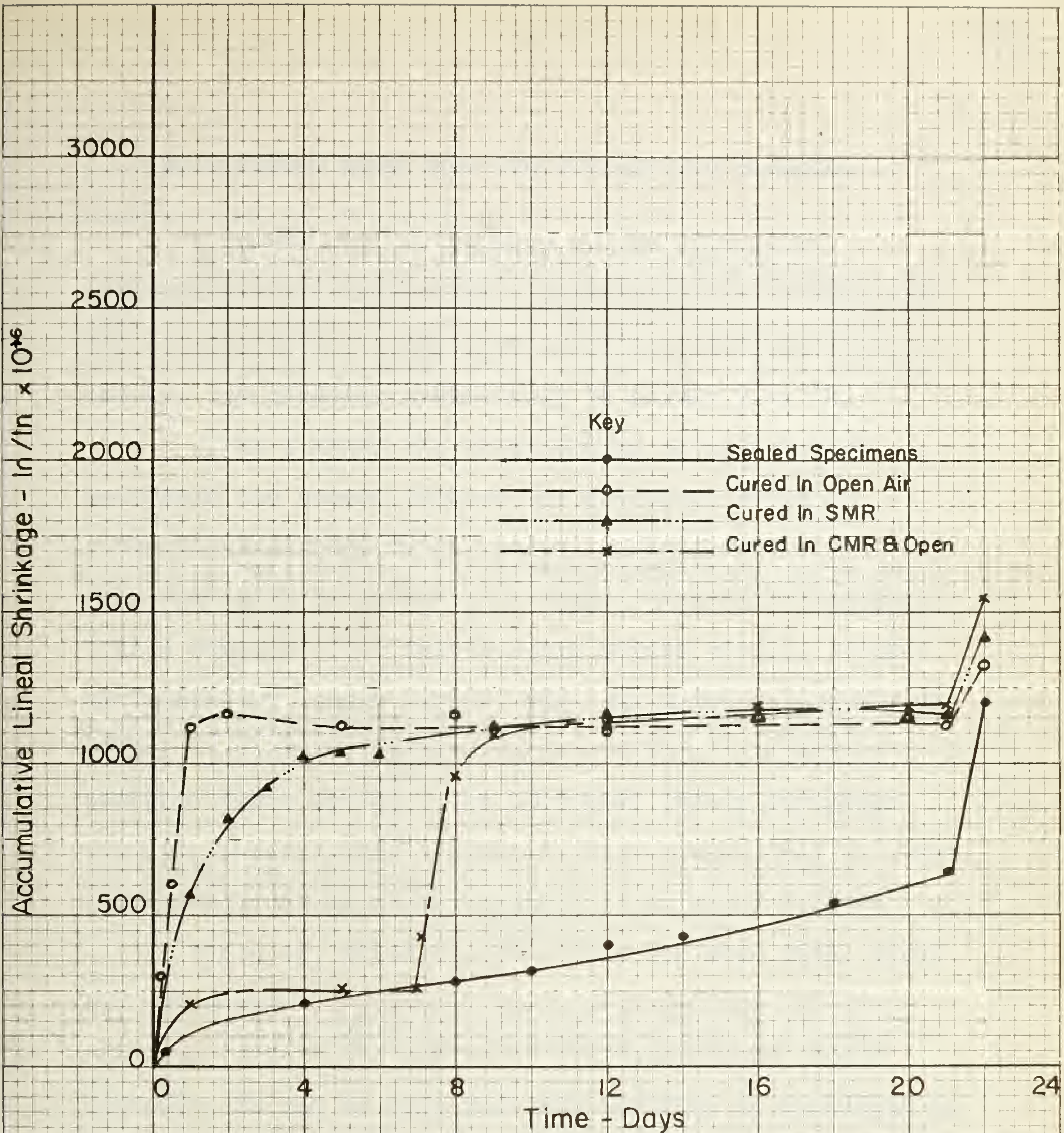
For Different Curing Conditions

Cement Content = 7 %

Moisture Content = 10.4 %

HENNIG PIT

PLATE 7



Accumulated Shrinkage vs. Time
For Different Curing Conditions
Compaction = 100% Standard Proctor
Moisture Content = 10.4%
Cement Content = 7%
HENNIG PIT

SOIL-CEMENT MADE FROM THE CAYWOOD PIT MATERIAL

A summary of the results of the laboratory investigation of soil-cement, made from the material from the Caywood pit, is contained in tables 12 to 14. These results are produced graphically on plates 9 to 13.

Plate 9 shows the relationship between lineal shrinkage and cement content for different moisture contents at mixing. In all cases there is an increase in shrinkage with an increase in cement content. It appears that a straight line relationship exists between lineal shrinkage and cement content when the moisture content at mixing is close to optimum for the soils. At moisture contents above optimum, the increased lineal shrinkage with increased cement content is more abrupt than the same relationship at moisture contents at or below optimum.

Plate 10, which is drawn from the same data, shows the relationship between lineal shrinkage and initial moisture content for specimens having different cement contents. It can be seen that the increase in shrinkage is more abrupt with increasing moisture content than it was for increasing cement content. This is particularly true for specimens having the higher cement contents. It appears that the lineal shrinkage increases in an orderly fashion with increased moisture content until optimum is reached. Past

optimum, the shrinkage increases abruptly with increased moisture content at mixing.

Plate 11 shows the relationship between lineal shrinkage and dry density for specimens prepared at different cement contents. There is no well defined trend apparent in these results. At cement contents of less than twelve percent, there is an indication of increased shrinkage with increased density. At a cement content of twelve percent, there is a slight trend in the opposite direction.

Plate 12 shows the relationship between lineal shrinkage and cement content for specimens which were cured under different conditions. The most significant aspect of these results is that the sealed specimens shrank much less than the specimens cured under the other conditions. This was particularly notable for specimens prepared at cement contents of six, eight and ten percent.

Plate 13 shows the relationship between shrinkage and time for similar specimens subjected to the four different curing conditions. After twenty-one days curing, the specimens were oven dried.

As with the Hennig pit material, the shrinkage which took place as a result of oven drying, appears to be a function of the moisture content at the time the specimens were placed in the oven. The sealed specimens had an average

moisture content of 13.3 percent. The specimens which were cured in the concrete moist room and open air, and the specimens which were cured entirely in the open had average moisture contents of 2.1 and 1.9 percent respectively. Those which were cured in the soils moist room had an average moisture content at the time of drying of 4.6 percent.

The pattern of shrinkage under each of the curing conditions was similar to that apparent in the Hennig pit soil-cement. However, it is noteworthy that the autogenous shrinkage of the sealed specimens of Caywood soil-cement was approximately one quarter of the total shrinkage, whereas it accounted for approximately one-half of the total shrinkage of the sealed Hennig soil-cement. The shrinkage characteristics of the other specimens are similar to the corresponding Hennig specimens except that the Caywood specimens took about twelve days to come to equilibrium in their environment.

THE RELATIVE IMPORTANCE OF THE FACTORS AFFECTING SHRINKAGE OF THE CAYWOOD PIT SOIL-CEMENT

The relative importance of the factors investigated, which affect shrinkage in the Caywood soil-cement, differ considerably from those which affect shrinkage in the Hennig soil-cement. On the same basis as that used for the

Hennig material these factors can be arranged in their relative order of importance as follows:

(1) Initial moisture content.

(2) Cement content.

(3) Curing condition.

(4) Compacted dry density.

TABLE 12

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

CAYWOOD PIT

TEST SERIES	CEMENT %	WATER %	DENSITY LBS/FT^3	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI X 10^{-6}	REMARKS
IA 1a	6	12.0	107.7	SMR	2230		.38	
b	6	12.0	108.4	SMR	2220	2225	.36	
2a	6	13.6	107.9	SMR	2580		.36	
b	6	13.6	109.1	SMR	2620	2600	.47	
3a	6	15.9	109.6	SMR	2780		.39	
b	6	15.9	107.6	SMR	2860	2820	.31	
4a	6	17.6	109.2	SMR	3080		.22	
b	6	17.6	109	SMR	3020	3050	.26	
IB 1a	8	11.7	107.3	SMR	2680		.40	
b	8	11.7	109.2	SMR	2710	2695	.43	
2a	8	13.6	109.2	SMR	2840		.49	
b	8	13.6	109.2	SMR	2810	2825	.39	
3a	8	15.5	108.3	SMR	3190		.27	
b	8	15.5	-	-	-	3190	-	broke
4a	8	17.6	110.1	SMR	3730		.34	
b	8	17.6	110.6	SMR	3510	3620	.30	
IC 1a	10	11.3	108.6	SMR	2840		.49	
b	10	11.3	108.3	SMR	2750	2795	.55	
2a	10	13.4	109.1	SMR	2980		.38	
b	10	13.4	108.1	SMR	2870	2925	.43	
3a	10	15.3	108.8	SMR	3220		.40	
b	10	15.3	108.4	SMR	3250	3235	.61	
4a	10	17.5	110.5	SMR	4380		.37	
b	10	17.5	108.5	SMR	4470	4425	.55	
ID 1a	12	11.7	106.3	SMR	2910		.36	
b	-	-	-	-	-	2910	-	broke
2a	12	13.6	108.8	SMR	3180		.58	
b	12	13.6	109.3	SMR	3100	3140	.67	
3a	12	15.8	108.8	SMR	3490		.47	
b	12	15.8	108.4	SMR	3380	3435	.45	
4a	12	17.4	109.5	SMR	4460		.38	
b	12	17.4	110	SMR	4550	4505	.43	

TABLE 13

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

CAYWOOD PIT

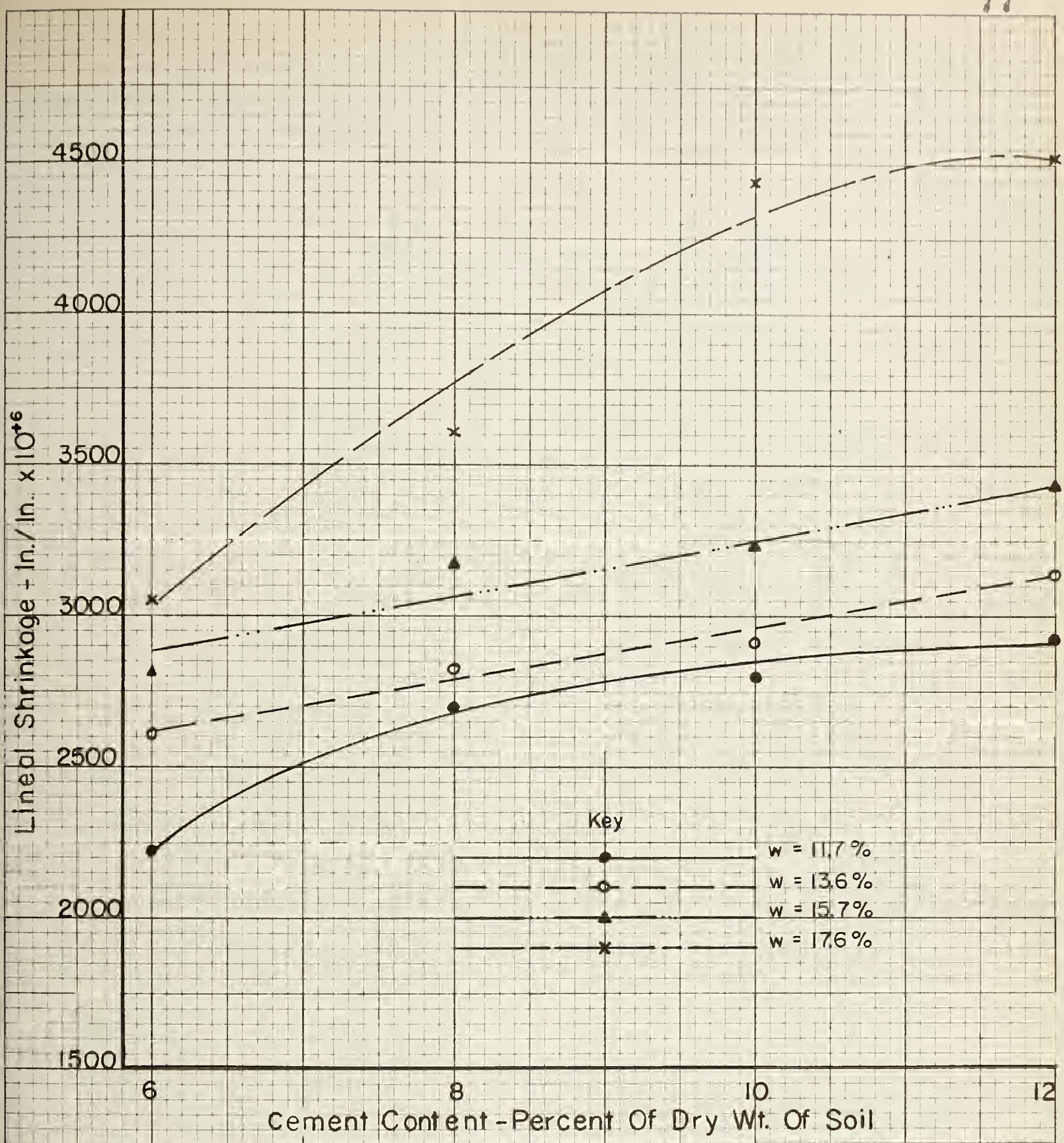
TEST SERIES	CEMENT %	WATER %	DENSITY LBS/FT³	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI X 10⁶	REMARKS
IIA 1a	-	-	-	-	-	-	-	broke
b	6	16.0	98.5	SMR	2330	2330	.19	
2a	-	-	-	-	-	-	-	broke
b	6	16.0	102.7	SMR	2340	2340	.25	
3a	6	15.9	109.6	SMR	2780		.39	
b	6	15.9	107.6	SMR	2860	2820	.31	IA3a&b
4a	6	15.9	110.9	SMR	2760		.55	
b	6	15.9	112	SMR	2710	2730	.47	
IIB 1a	8	16.1	97	SMR	2630		.25	
b	8	16.1	99.5	SMR	2730	2680	.24	
2a	8	15.3	104.3	SMR	3150		.30	
b	8	15.3	104.9	SMR	3340	3250	.34	
3a	8	15.5	108.3	SMR	3190	3190	.27	
b	-	-	-	-	-	-	-	IB3a&b broke
4a	8	15.3	112.5	SMR	3460		.55	
b	8	15.3	113.7	SMR	3230	3340	.51	
IIC 1a	10	15.2	98.2	SMR	3140		.33	
b	10	15.2	100.8	SMR	3070	3110	broke	
2a	10	15.1	104.5	SMR	3170		.36	
b	10	15.1	104.4	SMR	3280	3230	.33	
3a	10	15.3	108.8	SMR	3220		.40	IC 3a&b
b	110	15.3	108.4	SMR	3250	3240	.61	
4a	10	15.1	113.4	SMR	3500		.40	
b	10	15.1	113.3	SMR	3800	3670	.43	
IID 1a	12	15.1	97.6	SMR	3680		.32	
b	12	15.1	98.7	SMR	3700	3690	.36	
2a	12	15.3	107.8	SMR	3670		.49	
b	12	15.3	104.5	SMR	3650	3660	.55	
3a	12	15.8	108.8	SMR	3490		.47	ID3a&b
b	12	15.8	108.4	SMR	3380	3440	.45	
4a	12	15.0	112.3	SMR	3750		.61	
b	12	15.0	114.5	SMR	3680	3620	.76	

TABLE 14

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

CAYWOOD PIT

TEST SERIES	CEMENT %	WATER %	DENSITY LBS/FT	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI X 10^{-6}	REMARKS
IIIA1a	6	15.7	107.6	Open	2700		.26	
b	6	15.7	107.5	Open	2600	2650	.33	
2a	6	15.9	109.6	SMR	2780		.36	)IA2a
b	6	15.9	107.6	SMR	2860	2820	.47	)IA2b
3a	6	15.8	107.3	Sealed	1840		.20	
b	6	15.8	108.6	Sealed	1720	1780	.20	
4a	6	15.7	108.1	CMR	2540		.55	
b	6	15.7	108.1	CMR	2580	2560	.47	
IIIB1a	8	15.6	107.4	Open	3080		.43	
b	8	15.6	108.9	Open	3030	3055	.61	
2a	8	15.5	108.3	SMR	3190	3190	.49	)IB 2a
b	-	-	-	-	-	-	-	broke
3a	8	15.6	106.5	Sealed	2050		.26	
b	8	15.6	107.7	Sealed	1910	1980	.29	
4a	8	15.8	106.8	CMR	3090		.29	
b	8	15.8	107.8	CMR	3100	3095	.40	
IIIC1a	10	15.7	108.5	Open	3340		.34	
b	10	15.7	108.4	Open	3250	3295	.34	
2a	10	15.3	1088	SMR	3220		.38	)IC 2a
b	10	15.3	108.4	SMR	3250	3235	.43	)IC2b
3a	10	15.8	106.3	Sealed	2700		.22	
b	10	15.8	108.2	Sealed	2730	2715	.30	
4a	10	15.0	109.1	CMR	4160		.43	
b	10	15.0	108.8	CMR	3710	3935	.43	
IIID1a	12	15.6	108.7	Open	4180		.37	
b	12	15.6	109.1	Open	3790	4035	.40	
2a	12	15.8	108.8	SMR	3490		.48	)ID 2a
b	12	15.8	108.4	SMR	3380	3435	.57	)ID2b
3a	12	15.6	108.6	Sealed	3310		.61	
b	12	15.6	110.2	Sealed	3300	3305	.47	
4a	12	15.6	109.7	CMR	4340		.43	
b	12	15.6	110.0	CMR	4380	4360	.49	



Test Series 1

Lineal Shrinkage vs. Cement Content

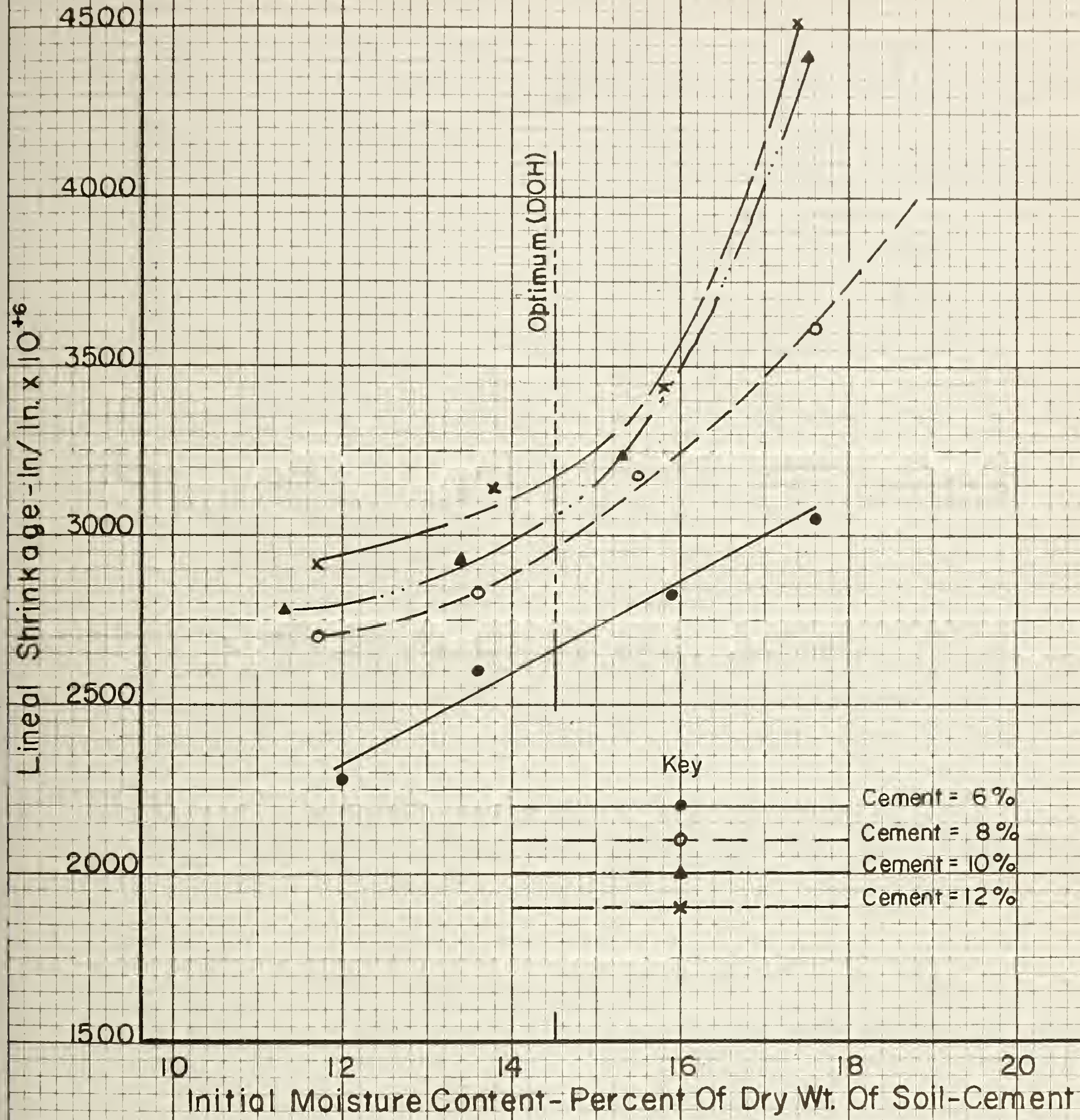
For Different Moisture Contents

Compaction = 100% Standard Proctor

Cured - Soils Moist Room

CAYWOOD PIT

PLATE 9



Test Series I

Lineal Shrinkage vs. Moisture Content

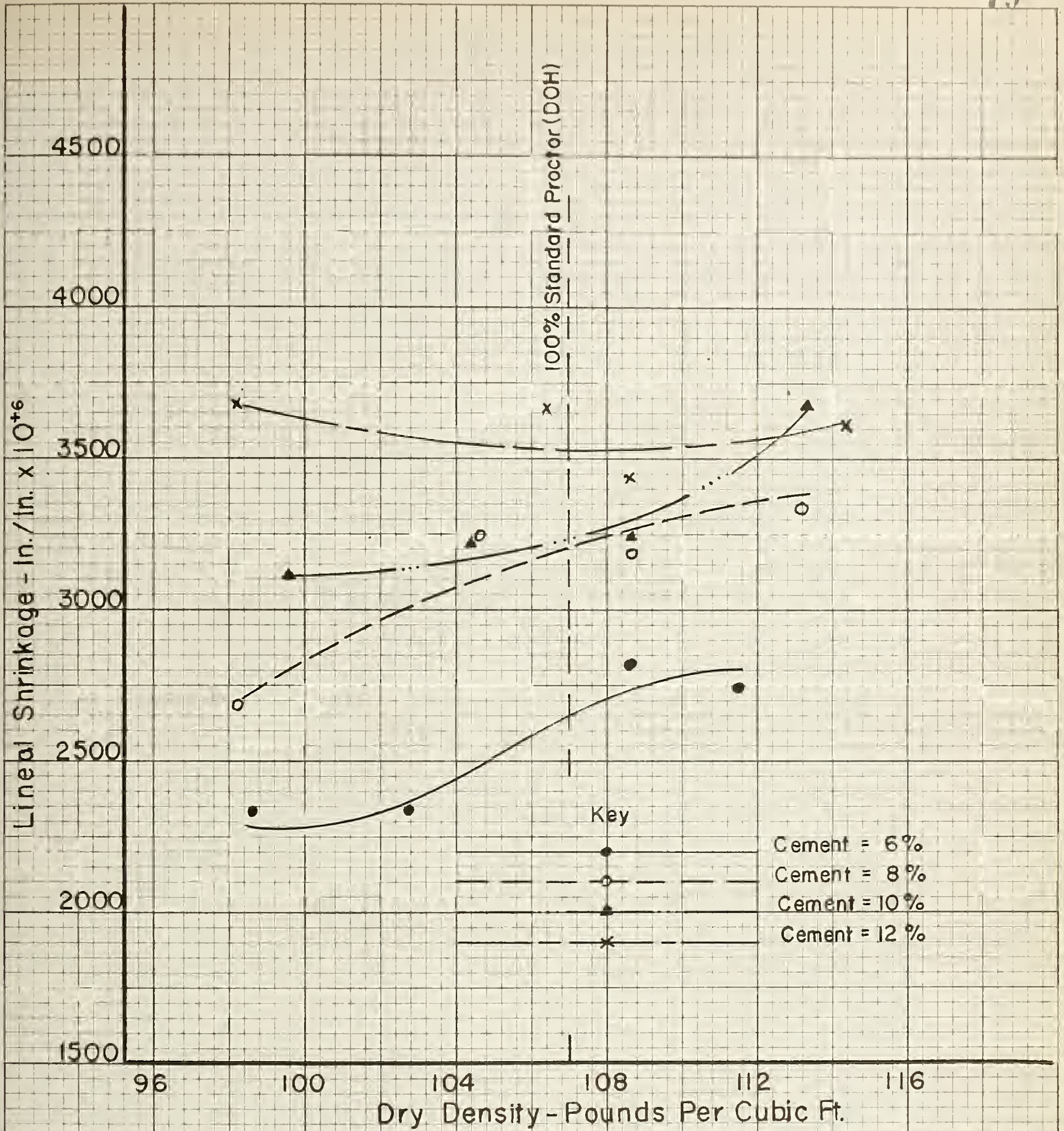
For Different Cement Contents

Compaction = 100% Standard Proctor

Cured Soils Moist. Room

CAYWOOD PIT

PLATE 10



Test Series II

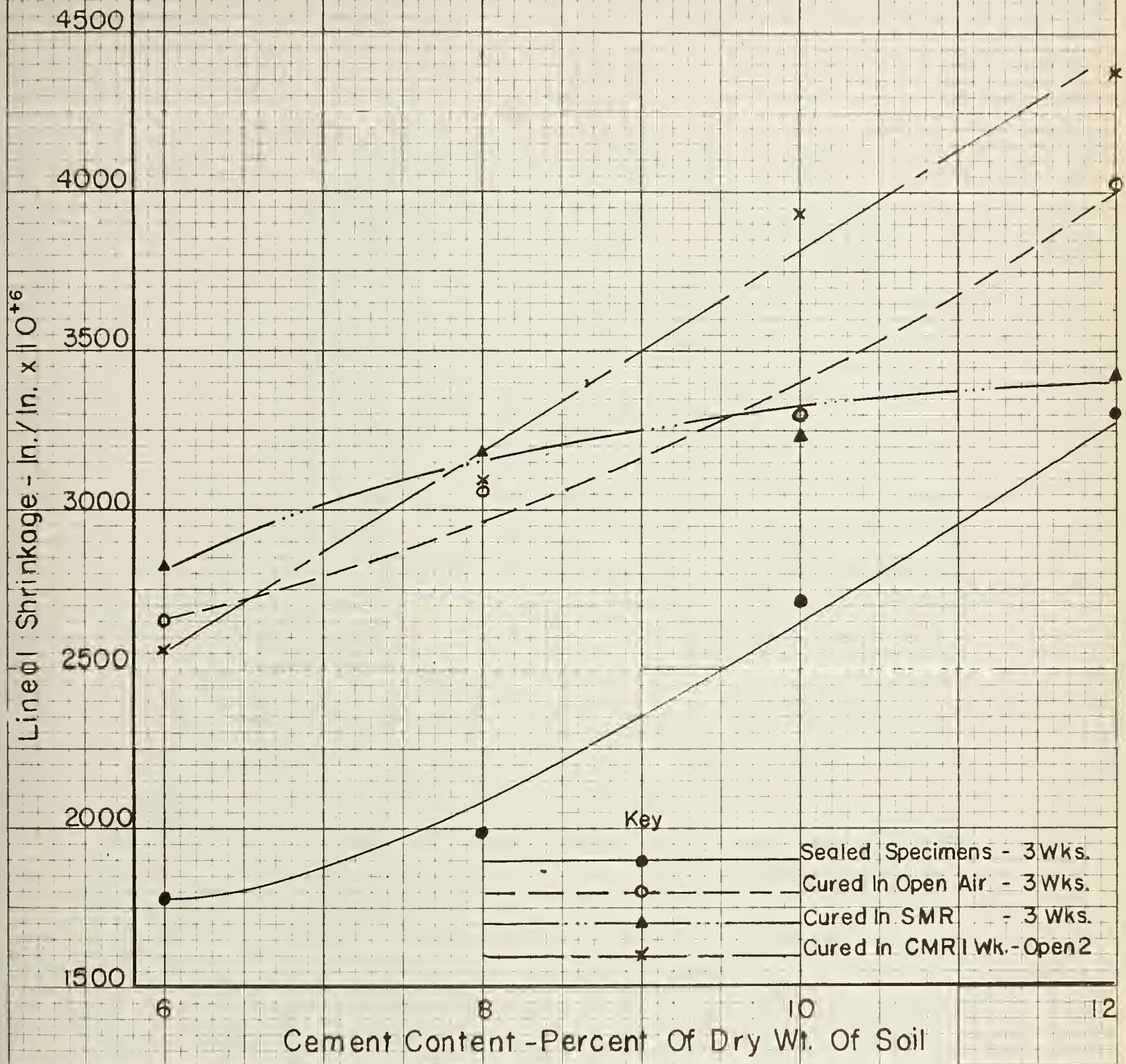
Lineal Shrinkage vs. Dry Density

For Different Cement Contents

Moisture Content = 15 %

Cured - Soils Moist Room

CAYWOOD PIT



Test Series

Lineal Shrinkage vs. Cement Content

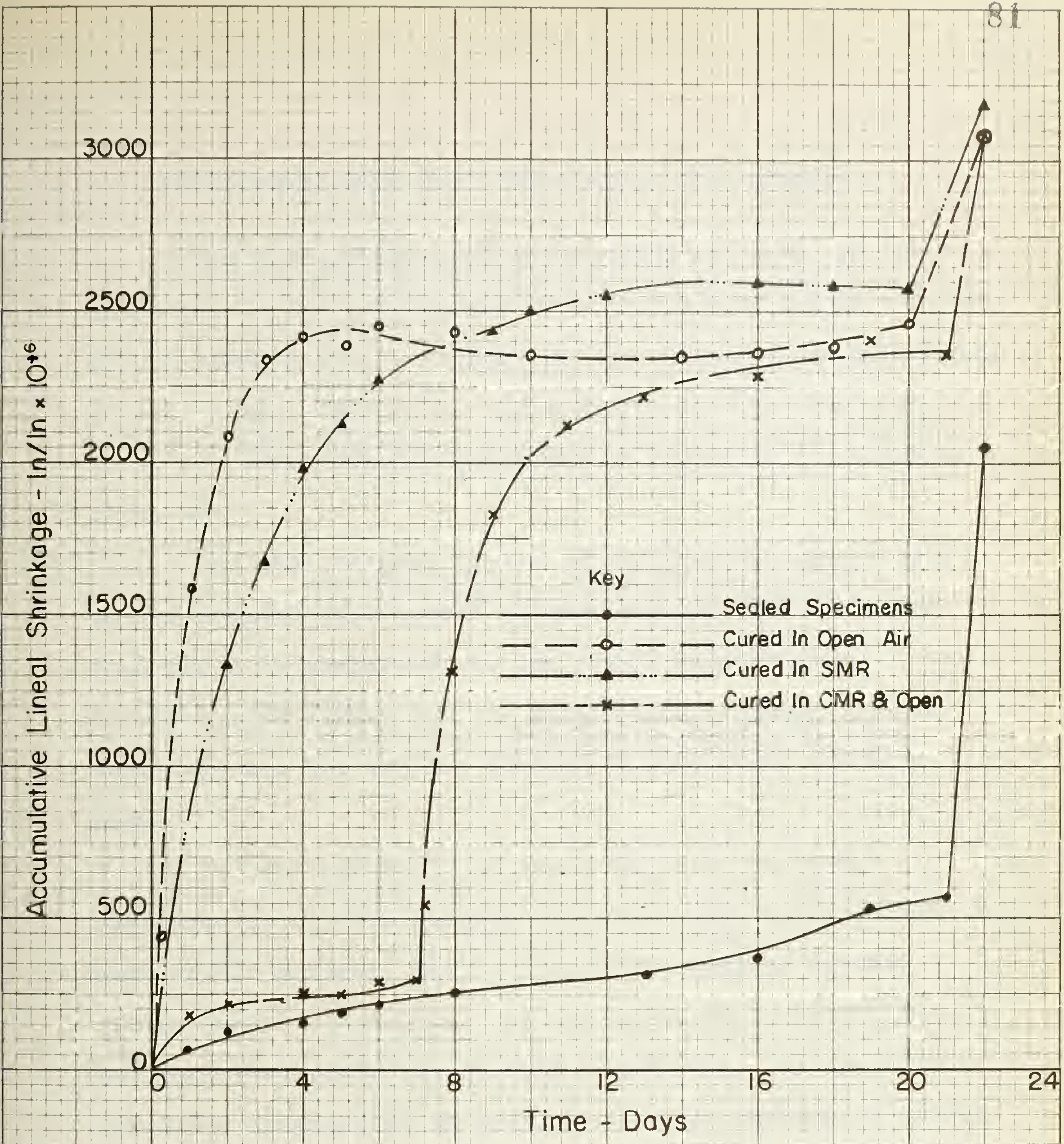
For Different Curing Conditions

Compaction = 100 % Standard Proctor

Moisture Content = 15%

CAYWOOD PIT

PLATE 12



Accumulative Shrinkage vs. Time
For Different Curing Conditions
Compaction = 100% Standard Proctor
Moisture Content = 15 %
Cement Content = 8 %
CAYWOOD PIT

PLATE 13

SOIL-CEMENT MADE FROM THE SHEPERT PIT MATERIAL

The soil-cement from the Shepert pit material was subjected to the same series of tests as that of the Caywood pit. A summary of the results of the shrinkage investigation of soil-cement made from this material is shown in tables 15 to 17. These results are produced graphically in plates 14 to 18.

The most notable aspect of all the series of tests on the Shepert soil-cement is that very little shrinkage took place in comparison to the other soil-cements. Moreover, the trends for the relationship between lineal shrinkage and the various factors investigated are very weak.

In test series I, it was impossible to obtain specimens which were prepared at low cement contents and high water contents. These mixes were repeated several times, however, each time the specimens were removed from the mold they broke immediately. Therefore, the data for specimens prepared at an initial moisture content of eleven percent are incomplete for cement contents of six and eight percent.

Plates 14 and 15 show a slight trend for a decrease in lineal shrinkage with increasing cement content and increasing initial moisture content. Similarly, plate 16 shows a tendency for shrinkage to decrease with increasing

dry density. Plate 17 shows that the curing conditions have very little effect on shrinkage although the sealed specimens shrank slightly less than those subjected to other conditions of curing.

Plate 18 shows the relationship between lineal shrinkage and time for the four conditions of curing. As can be seen, the pattern of shrinkage was erratic for all four conditions. The specimen which was stored at approximately one-hundred percent humidity actually expanded beyond its original length before it was placed in the open air.

After twenty-one days curing the specimens were placed in the oven for drying similar to the Caywood and Hennig specimens. Unlike the specimens from the other materials, the Shepert specimens did not appear to shrink in accordance with the moisture content before drying. Those which were stored in the open air, after one week in the concrete moist room, and those which were stored for the entire three weeks in the open, had average moisture contents before drying of 0.8 and 0.4 percent respectively. These specimens did not shrink when they were oven dried. The specimens which were sealed and those which were cured in the soils moist room had average moisture contents of 4.9 and 1.5 percent respectively. Furthermore, the specimens which were cured in the soils moist room shrank more than those which were sealed when they were placed in the oven.

THE RELATIVE IMPORTANCE OF THE FACTORS AFFECTING SHRINKAGE IN THE SHEPERT SOIL-CEMENT

From the results of the investigation on the Shepert soil-cement it is difficult to pick the most significant factor affecting shrinkage. It appears that the compacted dry density is the most significant variable for this material. The cement content, initial moisture content and curing conditions appear to have very little effect on shrinkage within the range of variables investigated.

TABLE 15

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

SHEPERT PIT

TEST SERIES	CEMENT %	WATER %	DENSITY % OF S.P.	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI X 10^{-6}	REMARKS
IA 1a	6	4.65	100	SMR	630		.55	
b	6	4.65	"	SMR	500	565	.58	
2a	6	7.35	"	SMR	440		.47	
b	6	7.35	"	SMR	400	420	.49	
3a	6	9.20	"	SMR	550		.36	
b	6	9.20	"	SMR	500	525	.37	
4a	-	-	-	-	-	-	-	broke
b	-	-	-	-	-	-	-	broke
IB 1a	8	5.20	"	SMR	530		.58	
b	8	52	"	SMR	600		.53	
2a	8	7.60	"	SMR	570	520	.87	
b	8	7.60	"	SMR	470	520	.55	
3a	8	9.50	"	SMR	700		.53	
b	8	9.50	"	SMR	410	555	.43	
4a	-	-	-	-	-	-	-	broke
b	-	-	-	-	-	-	-	broke
IC 1a	10	5.00	"	SMR	390		.87	
b	10	5.00	"	SMR	460	420	.76	
2a	10	7.60	"	SMR	490		.67	
b	10	7.60	"	SMR	460	475	.51	
3a	10	9.50	"	SMR	420		.40	
b	10	9.50	"	SMR	360	390	.61	
4a	10	11.1	"	SMR	340	340	.40	
b	-	-	-	-	-	-	-	broke
ID 1a	12	5.50	"	SMR	480		.87	
b	12	5.50	"	SMR	500	490	.71	
2a	12	7.30	"	SMR	420		.51	
b	12	7.30	"	SMR	400	410	.76	
3a	12	9.20	"	SMR	350		.64	
b	12	9.20	"	SMR	340	345	.78	
4a	-	-	-	-	-	-	-	broke
b	12	11.4	"	SMR	330	330	.43	

TABLE 16

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

SHEPERT PIT

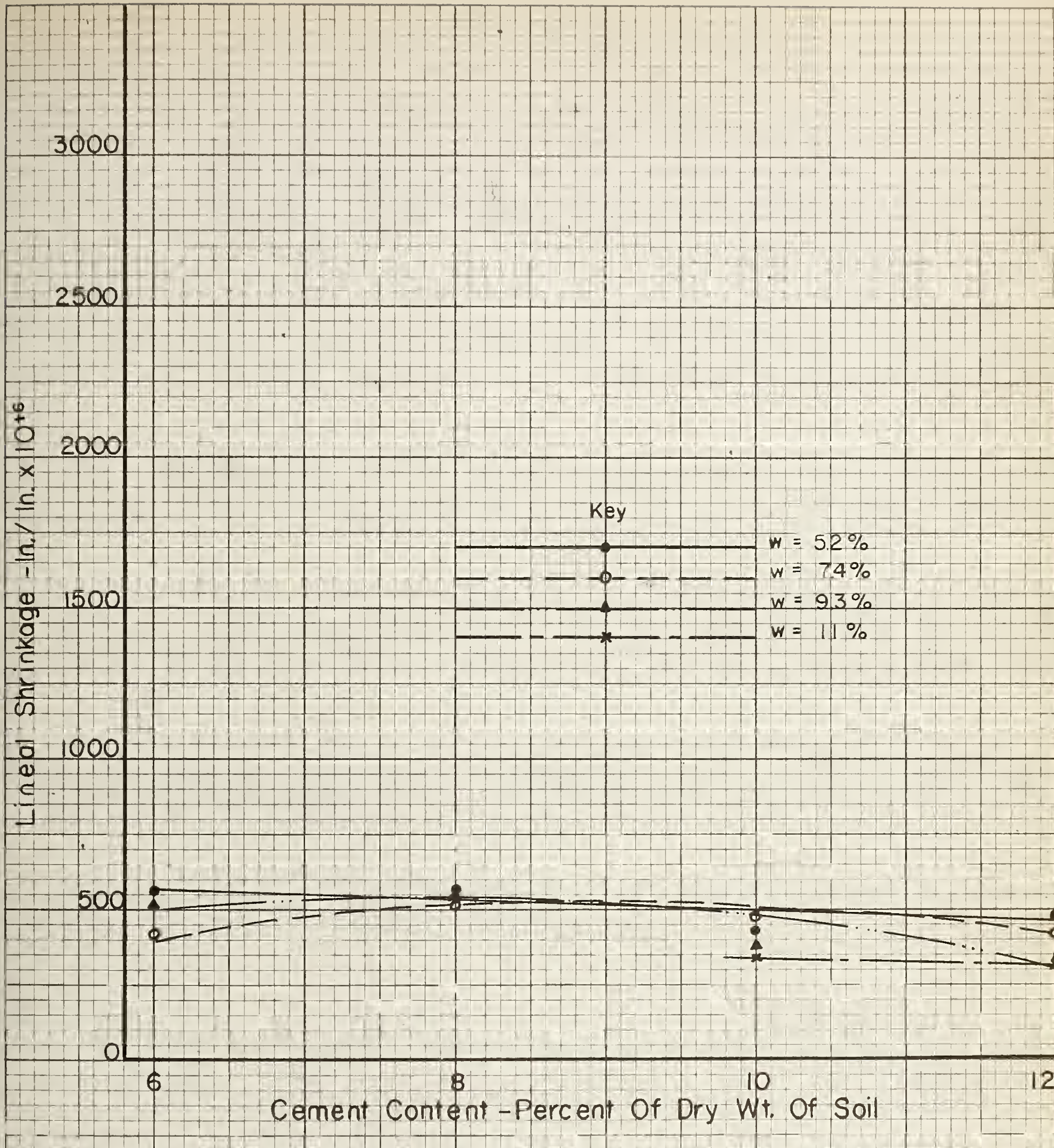
TEST SERIES	CEMENT %	WATER %	DENSITY % OF S.P.	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI x 10^{-6}	REMARKS
IIA 1a	6	7.2	95	SMR	530	530	.58	
b	-	-	-	-	-	-	-	broke
2a	6	7.4	100	SMR	440		.47	)IA2a&b
b	6	7.4	100	SMR	400	420	.49	)
3a	6	7.4	105	SMR	390		.58	
b	6	7.4	105	SMR	410	400	.55	
4a	6	8.1	110	SMR	350		.49	
b	6	8.1	110	SMR	300	325	.53	
IIB 1a	8	7.2	95	SMR	610		.71	
b	8	7.2	95	SMR	580	595	.53	
2a	8	7.6	100	SMR	570		.87	)IB2a&b
b	8	7.6	100	SMR	470	520	.55	)
3a	8	7.2	105	SMR	430		.67	
b	8	7.2	105	SMR	440	435	.55	
4a	8	7.1	110	SMR	380		.58	
b	8	7.1	110	SMR	420	400	.71	
IIC 1a	10	7.2	95	SMR	640		.76	
b	10	7.2	95	SMR	610	625	.81	
2a	10	7.6	100	SMR	490		.67	)IC2a&b
b	10	7.6	100	SMR	460	475	.51	)
3a	10	8.3	105	SMR	440		1.01	
b	10	8.3	105	SMR	380	410	.61	
4a	10	7.5	110	SMR	400		.61	
b	10	7.5	110	SMR	400	400	1.35	
IID 1a	12	7.8	95	SMR	700		.87	
b	12	7.8	95	SMR	680	690	.76	
2a	12	7.3	100	SMR	420		.51	)ID2a&b
b	12	7.3	100	SMR	400	410	.76	)
3a	12	7.8	105	SMR	620		-	
b	12	7.8	105	SMR	590	605	.67	
4a	12	7.3	110	SMR	420		.61	
b	12	7.3	110	SMR	500	460	.61	

TABLE 17

SUMMARY OF SOIL-CEMENT SHRINKAGE DATA

SHEPERT PIT

TEST SERIES	CEMENT %	WATER %	DENSITY % OF S.P.	CURING CONDITIONS	SHRINKAGE MILLIONTHS	AVERAGE a & b	E PSI X 10^{-6}	REMARKS
IIIA 1a	6	7.40	100	Open	360	360	-	
b	-	-	"	-	-	-	-	broke
2a	6	7.40	"	S.R	440		.41	)IA 2a
b	6	7.40	"	S.R	400	420	.49	)IA 2b
3a	6	8.40	"	C.R	480	480	-	
b	-	-	"	-	-	-	-	broke
4a	-	-	"	-	-	-	-	broke
b	6	7.70	"	Sealed	360	360	.51	
IIIB 1a	8	7.70	"	Open	210		-	
b		7.70	"	Open	210	210		
2a	8	7.60	"	S.R	570		.87	)IB 2a
b	8	7.60	"	S.R	470	520	.55	)IB 2b
3a	8	8.40	"	C.R	250		.37	
b	8	8.40	"	C.R	290	270	.61	
4a	8	7.70	"	Sealed	230		1.10	
b	8	7.70	"	Sealed	210	220	.65	
IIIC 1a	10	7.40	"	Open	350		.42	
b	10	7.40	"	Open	320	335	.38	
2a	10	7.60	"	S.R	490		.67	)IC 2a
b	10	7.60	"	S.R	460	475	.51	)IC 2b
3a	10	6.80	"	C.R	520		1.01	
b	10	6.80	"	C.R	520	520	.81	
4a	10	7.40	"	Sealed	320		.51	
b	10	7.40	"	Sealed	360	290	.61	
IIID 1a	12	7.30	"	Open	490	490	.55	
b	-	-		-	-	-	-	broke
2a	12	7.30	"	S.R	400		.51	)ID 2a
b	12	7.30	"	S.R	400	410	.76	)ID 2b
3a	12	7.90	"	C.R	640		.93	
b	12	7.90	"	C.R	550	595	.67	
4a	12	7.60	"	Sealed	450		.87	
b	12	7.60	"	Sealed	430	440	.87	



Test Series I

Lineal Shrinkage vs. Cement Content

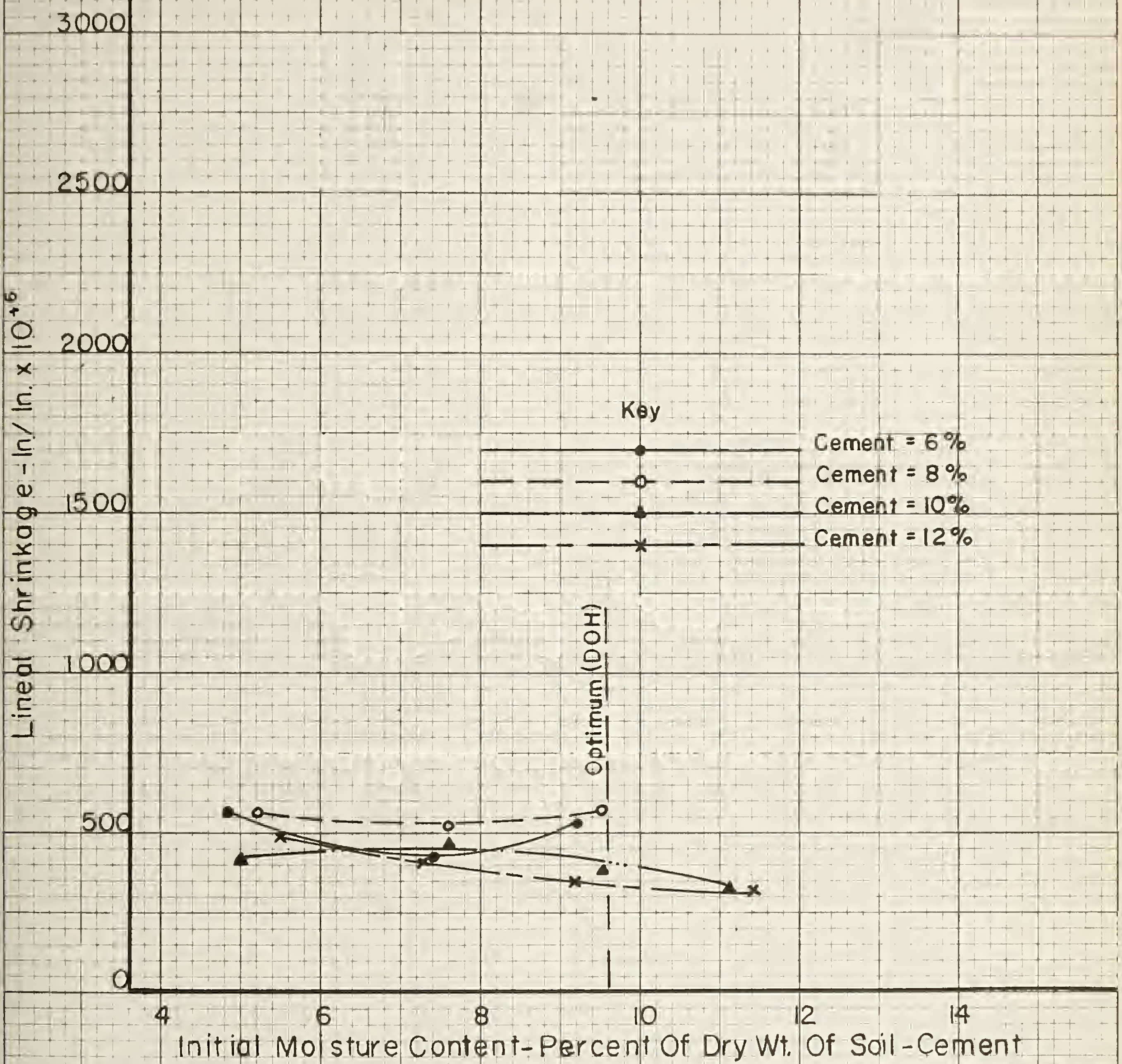
For Different Moisture Contents

Compaction = 100% Standard Proctor

Cured - Soils Moist Room

SHEPERT PIT

PLATE 14



Test Series I

Lineal Shrinkage vs. Moisture Content

For Different Cement Contents

Compaction = 100% Standard Proctor

Cured Soils Moist. Room

SHEPERT PIT

PLATE 15

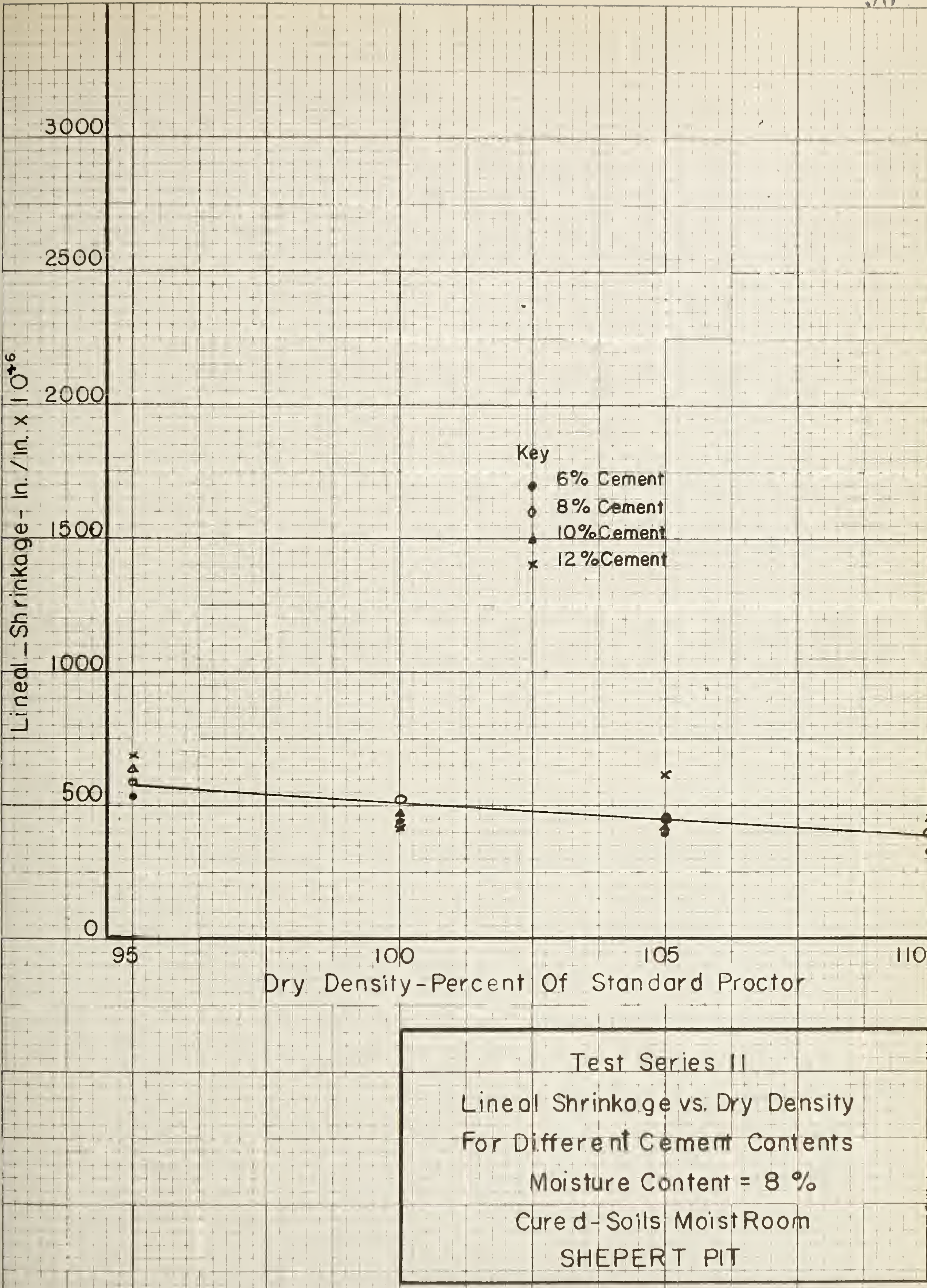
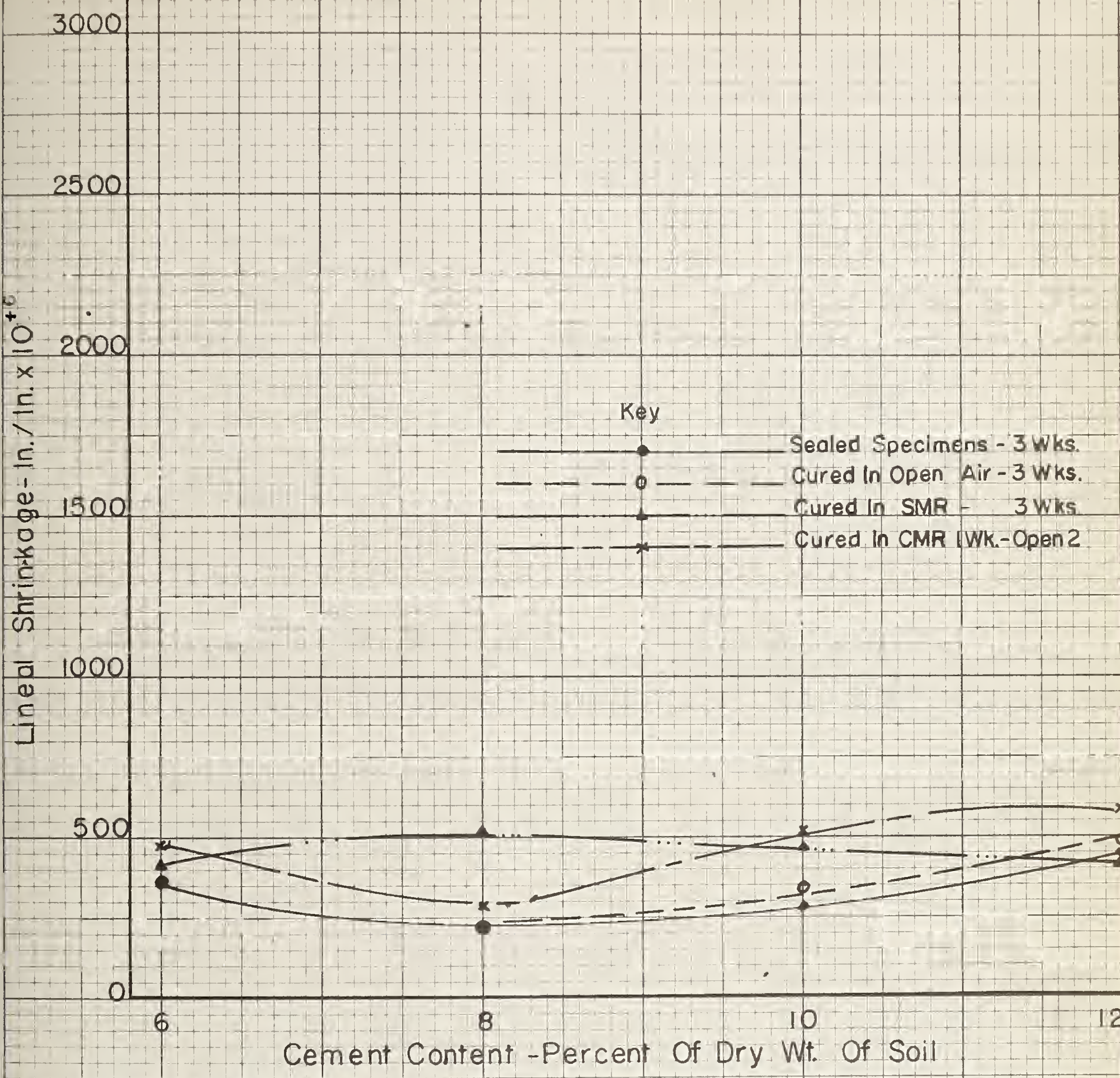

3000
2500
2000
1500
1000
500
0
Lineal _ Shrinkage - In. / In. x 10^{-6}
Key
6% Cement
8% Cement
10% Cement
12% Cement
95
100
105
110
Dry Density - Percent Of Standard Proctor
Test Series II
Lineal Shrinkage vs. Dry Density
For Different Cement Contents
Moisture Content = 8 %
Cured - Soils Moist Room
SHEPERT PIT

PLATE 16



Test Series III

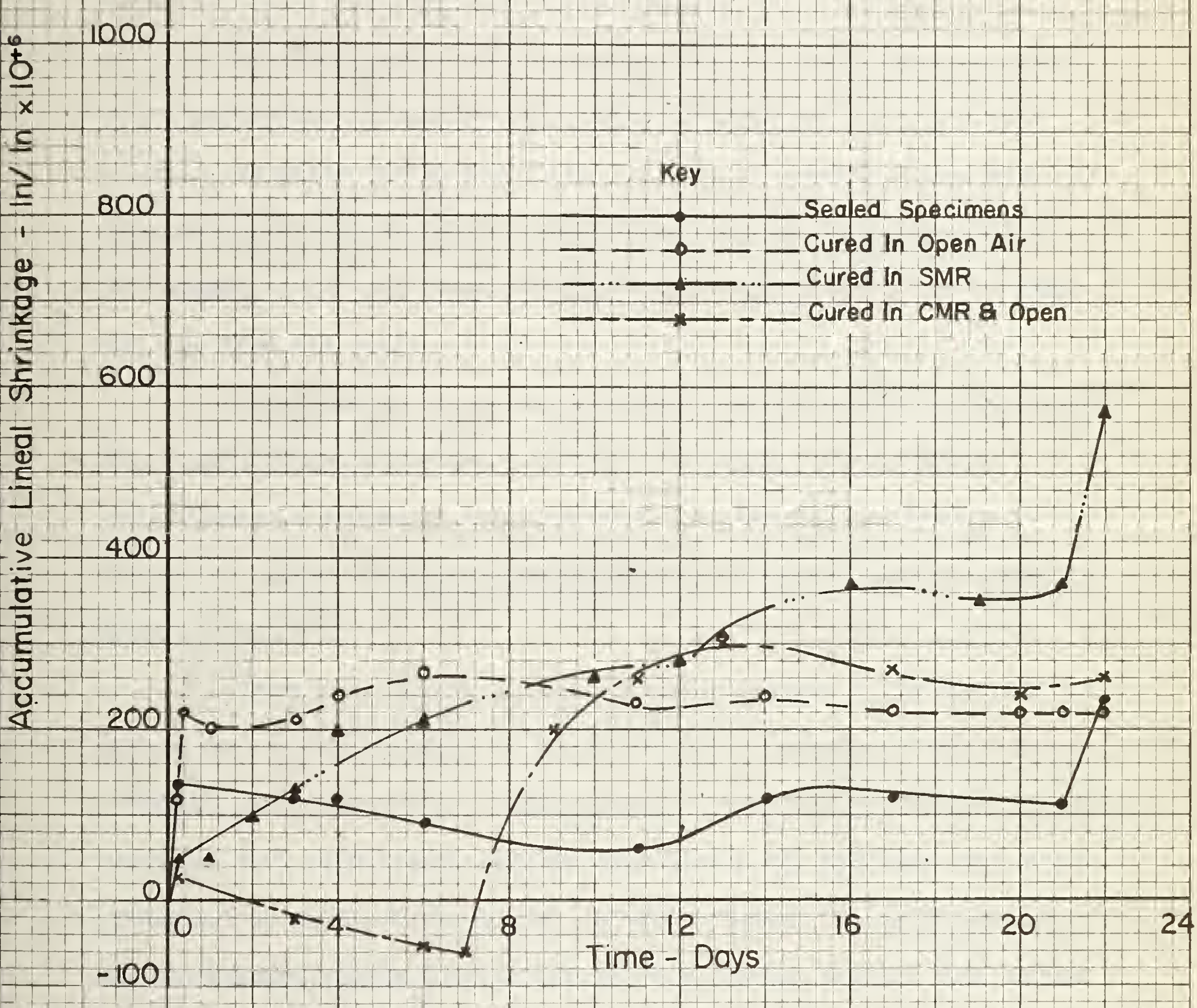
Lineal Shrinkage vs. Cement Content For Different Curing Conditions

Compaction = 100 % Standard Proctor

Moisture Content = 8 %

SHEPERT PIT

PLATE 17



Accumulative Shrinkage vs. Time
For Different Curing Conditions
Compaction = 100 % Standard Proctor
Moisture Content = 8 %
Cement Content = 8 %
SHEPERT PIT

PLATE 18

COMPARISON OF SHRINKAGE CHARACTERISTICS OF THE THREE SOIL-CEMENTS

The results of this investigation indicate that the most isgnificant factor affecting shrinkage of the soil-cements studied is grain size. The soil-cement from the Caywood pit shrank approximately twice as much as that of the Hennig pit and approximately six times as much as that of the Shepert pit.

Since there were only three soils investigated, there was insufficient information to establish a definite relationship between grading and the lineal shrinkage. However, there was an indication that such a relationship does exist.[1]

Plate 19, which is drawn from plates 1, 9 and 14, shows the relationship between lineal shrinkage and cement content for the three soil-cements investigated. The moisture content for each soil-cement was close to optimum for that particular soil. This plate readily shows the difference in shrinkage characteristics of the three soils. The trend

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[1] Appendix F shows the trend between lineal shrinkage and a grading modulus for the three soils investigated. The simplifying assumptions used to determine the grading modulus, and the scant data, preclude the inclusion of this relationship in the body of the text.

of increased shrinkage with increased cement content is apparent for the Caywood and Hennig soil-cement. It is, however, more significant for the Hennig material. The Shepert pit shows little sensitivity to change in cement content within the range investigated.

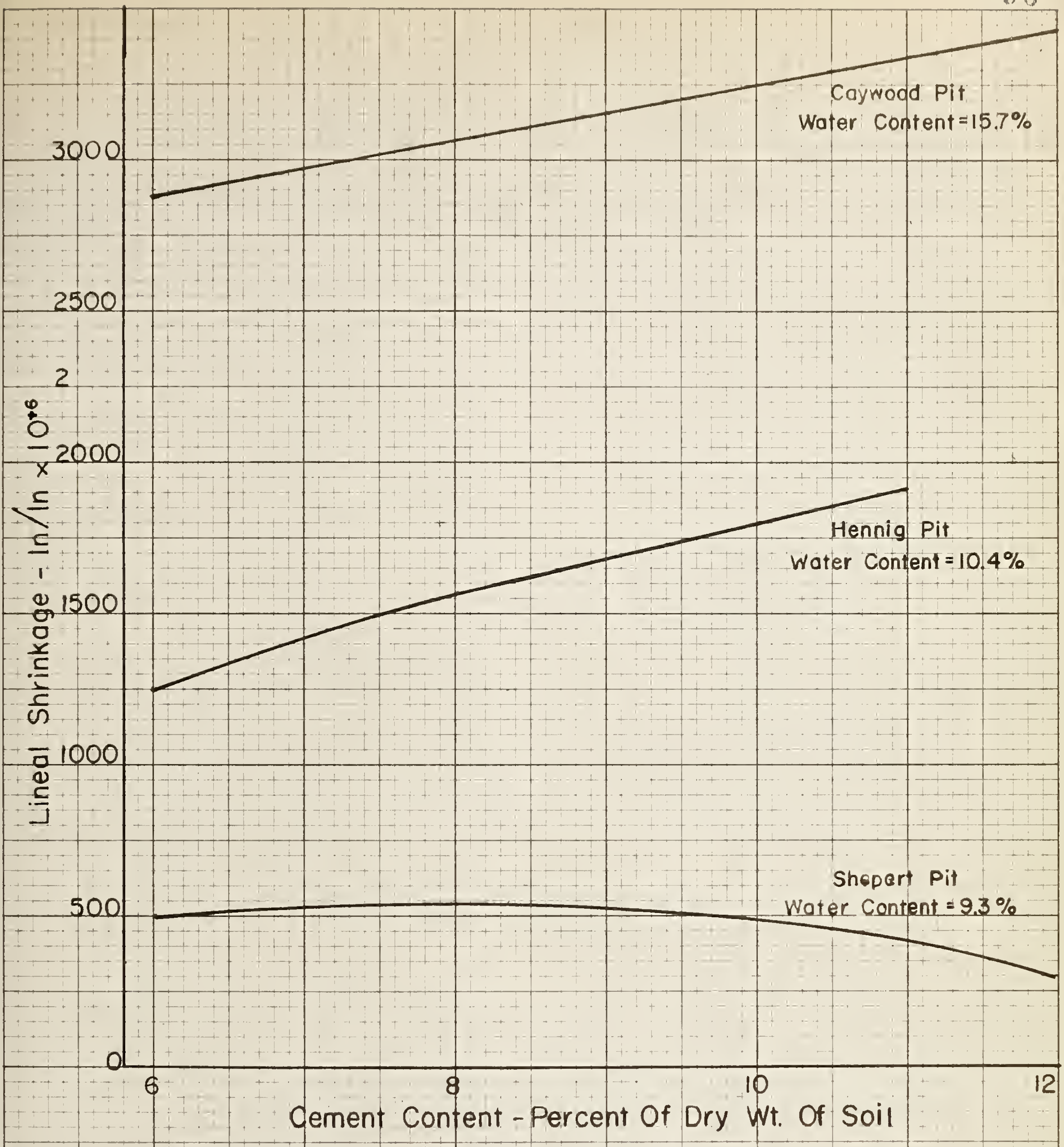
Plate 20 is drawn from plates 2, 10 and 13. It shows the relationship between lineal shrinkage and initial moisture content for the three soil-cements. The cement content of each mix is approximately the design cement content arrived at by the Department of Highways for the projects on which these soils were used.

This plate clearly shows that the finest soil is the most sensitive to a change in initial moisture content. The Hennig soil-cement shows an increase in shrinkage with increasing initial moisture content but is less abrupt than the Caywood soil-cement. The Shepert soil-cement shows little sensitivity to a change in initial moisture content.

Plate 21 shows a comparison of the relationships between lineal shrinkage and percentage of standard Proctor dry density for the soil-cements investigated. This plate is drawn from plates 3, 11 and 16. The cement and water content for each soil-cement is approximately equal to that arrived at by the design staff of the Department of Highways.

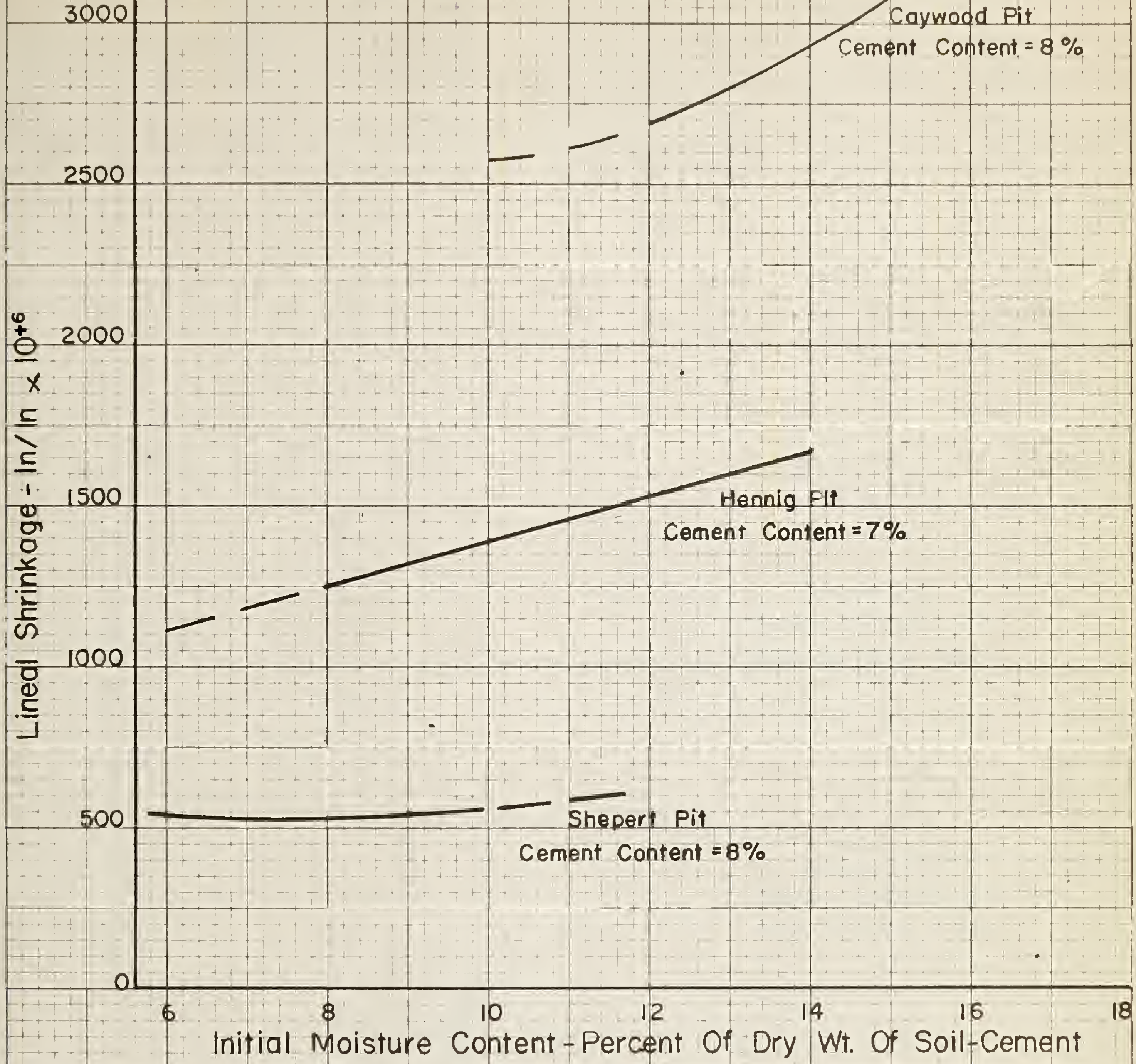
It can be seen that the soil-cement from the Hennig

pit is the most sensitive to a change in density. Lineal shrinkage decreased appreciably with an increase in density. The Shepert soil-cement showed a slight trend in the same direction; however, the Caywood soil-cement at this particular mix showed a fairly well defined trend in the opposite direction.



Lineal Shrinkage vs. Cement Content
For Three Different Soils
Compaction = 100% Standard Proctor
Cured - Soils Moist Room

PLATE 19



Lineal Shrinkage vs. Moisture Content
For Three Different Soils
Compaction = 100% Standard Proctor
Cured - Soils Moist Room

PLATE 20

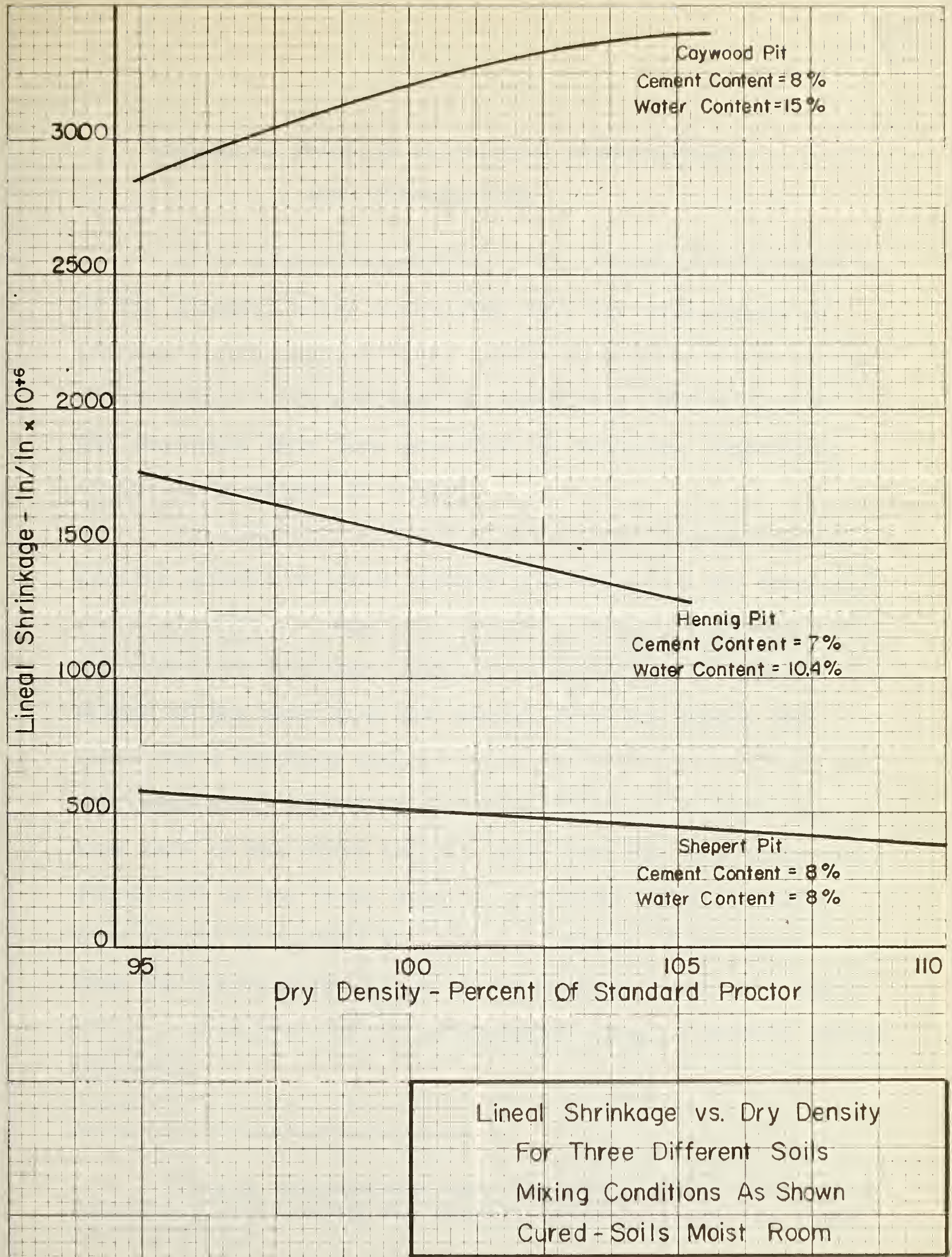

Caywood Pit
Cement Content = 8 %
Water Content = 15 %
Hennig Pit
Cement Content = 7%
Water Content = 10.4%
Shepert Pit
Cement Content = 8 %
Water Content = 8 %
3000
2500
2000
1500
1000
500
0
Lineal Shrinkage - In/In x 10+6
95
100
105
110
Dry Density - Percent Of Standard Proctor
Lineal Shrinkage vs. Dry Density
For Three Different Soils
Mixing Conditions As Shown
Cured - Soils Moist Room

PLATE 21

SOURCES OF ERROR IN LABORATORY INVESTIGATION AND CALCULATIONS

It is almost impossible to do a quantitative analysis of the probable error associated with the measurement of shrinkage. The most probable source of error was due to the sensitivity of the specimen and measuring device. Most of the specimens were very sensitive to handling, especially in the early stages of curing.

The other main source of error was in achieving the desired initial moisture content and compacted dry density.[1] The proportion of cement was based on the air dry weight of the soil. The water was based on a percentage of the dry weight of the soil plus the cement. When the sample was taken for a moisture content determination after mixing, it was immediately placed in the oven. However, between the time that it was mixed and the time that the free water was driven off in the oven, some of the water would be taken into solids by partial hydration of cement. Thus, apart from the limiting precision of the scales, there is a small error in moisture content determination due to partial cement hydration.

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[1] Sample calculations and percentage errors associated with mix proportioning and density determinations are shown in Appendix E.

The estimated dry density of the specimens was based on the air dried weight of the soil and the cement. The actual density was determined by immersion in mercury, after the specimen had been oven dried. During the curing period the dry density would increase, particularly at the higher cement contents, due to the hydration of the cement. It has been shown that in seven days, cement hydration can account for an increase of one percent in the dry density of normal soil-cement.[2] Thus the densities calculated by the mercury immersion method involved an error due to hydration of cement, as well as the probable error due to limiting precision. No attempt was made to correct for the change in density due to hydration since it was not known to what extent variations in cement content and moisture content would affect the figure of one-percent.

The soil-cement which was made from the Caywood and Hennig material had a closely knit surface texture. The mercury immersion method of density determination worked well with these soils. However, the Shepert soil-cement had an open texture and was very porous. The mercury permeated the soil-cement so that this method of density determination could not be used. Therefore, the relation between dry density and lineal shrinkage, for the Shepert soil-cement,

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[2]Domaschuk, L., Op. Cit. p.50.

was based on the calculated percentage of Standard Proctor density, when the specimen was formed.

The method which was used to determine the center-point deflection of the specimens, under a concentrated load, involved several sources of error. The main source of error was in the non-uniformity of the specimens. Quite often when the specimens were removed from the mold, a small amount of the soil-cement would stick to the sides of the mold. This did not affect the lineal shrinkage which the specimen underwent but it did affect the deflection since it reduced the cross-sectional area. These variations in cross-sectional areas, even though slight, appeared to have a considerable influence on the deflection of the specimen under load. Moreover, in many specimens there was a slight variation in density throughout the specimen length. This had no apparent effect on lineal shrinkage but it would tend to have a much greater affect on flexural strength. For these reasons the deflection modulus determined by this method can be considered no more than a very rough indication of the relative strength of the specimens. The deflection modulus was obtained by loading the specimens in increments up to a point which would give a measureable deflection but which would not break the specimen. Although the modulus of rupture would have given a better indication of strength, it was preferable to have a controlled break which would

give three portions for density determinations. Those specimens which did break under loading, were so badly shattered that it was difficult to salvage suitable portions for density determinations. Since strength was not being directly considered as a variable factor affecting shrinkage, it was felt that obtaining an accurate measurement of density was more important than obtaining a more refined indication of strength.

The calculations for E were based on the equation for the deflection of a simple beam under a concentrated load at the center point.[3]

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[3]Sample calculations are shown in Appendix E.

THE THERMAL COEFFICIENT OF EXPANSION FOR THE THREE SOIL-CEMENTS

The determination of the thermal coefficient of expansion was not undertaken as an integral part of this study. However, since the various conditions of curing were subjected to slight changes in temperature it was felt worthwhile to investigate to what extent a small change in temperature would change the length of the specimen.

The thermal coefficient of expansion for the three soils was found to be approximately the same. Tests were carried out only on the specimens which corresponded to the design mix as determined by the Department of Highways. The Hennig pit soil-cement had a thermal coefficient of 6.8 millionths per degree fahrenheit. The Caywood and Shepert soil-cements both had coefficients of 7.1 millionths per degree fahrenheit.[4] Thus, a change of one centigrade degree, in any of the curing temperatures, could account for a change in length of the specimens of approximately 12 millionths.

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[4]Calculations for the thermal coefficients are shown in Appendix E.

CONCLUSIONS FROM LABORATORY INVESTIGATION

Upon reviewing the results of the laboratory investigation, it appears that the oven drying of the specimens was a fallacy in the technique. This was due to the difference in the degree of hydration which took place under the three curing conditions. The relative percentage of cement hydration after twenty-one days is not comparable to the percentage of cement hydration which might have occurred over a much longer period, had the specimens been left in their environments.

On the basis of the oven drying technique which was used, the following conclusions have been drawn from the laboratory results.

(1). The most significant factor affecting the shrinkage of the three soil-cements investigated is the grain size. The finer the sand, the greater the amount of lineal shrinkage.

(2). Variations in the percentage of initial moisture content have different effects on soil-cement, depending on grain size. The initial moisture content is the most important factor affecting shrinkage in fine grained soil-cements. As the grain size increases, the importance of initial moisture content on shrinkage decreases.

(3). An increase in cement content will generally result in an increase in shrinkage. It is more significant for medium fine sands than for very fine sands. Coarse

sands show little sensitivity to increased cement content.

(4). Soil-cements produced from medium or coarse sands show a decreased shrinkage with an increased density. Soil-cements produced from very fine sands show an increase in shrinkage with increased density.

(5). The curing condition of the soil-cement appears to be an important factor affecting lineal shrinkage. The best curing condition to reduce shrinkage appears to be a good air-tight seal.

(6). The amount of drying shrinkage which occurs in soil-cement depends upon the moisture content at the time of drying and the length of time and condition of curing. If the soil-cement has been allowed to hydrate slowly and form a stable gel, less shrinkage will occur upon drying.

CHAPTER VI

COMPARISON OF SHRINKAGE IN THE SOIL-CEMENTS INVESTIGATED WITH SHRINKAGE IN CONCRETE

GENERAL COMPARISONS

In chapter III, it was shown that shrinkage in concrete was largely produced by cement hydration, or autogenous shrinkage, and shrinkage due to moisture losses. The amount of autogenous shrinkage depends primarily on the amount and nature of the cement gel. The shrinkage due to moisture losses is influenced by: (1) the composition and fineness of the cement, (2) cement and water contents, (3) the type and gradation of the aggregate, and (4) the temperature and humidity. It was also shown that the largest single factor affecting shrinkage in concrete was the water content. The most important factor causing concrete made from different aggregates to shrink different amounts, appears to be the compressibility of the aggregate.

It has been pointed out that an important difference between concrete and soil-cement is that the water/cement ratio concept as used in concrete work is not applicable to soil-cement. The strength of concrete which is incompletely packed cannot be related to its water/cement ratio since the water/cement ratio concept applies only to mixtures in which

all air voids are expelled. Therefore, no such relationship can be expected to apply to unsaturated soil-cement mixtures.[1]

In contrast to this opinion, a laboratory investigation carried out in Texas, indicated that for soil-cements, "strength and rigidity and other associated properties, decrease with the water-cement ratio, according to Abram's Law."[2]

The effect of moisture content on the quality of soil-cement largely arises from its influence on compaction, rather than its relation to cement content. In concrete an increase in cement at a constant water content does not increase shrinkage. This relationship cannot be expected in soil-cement since, even at increased cement contents, the mixture will have more than an abundancy of water to hydrate the cement. Therefore, an increase in cement content in soil-cement should increase shrinkage.

The autogenous shrinkage of sealed concrete appears to be similar to the shrinkage which occurred in the sealed

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[1]Larnach, W.J., "Relationship Between Dry Density, Voids/Cement Ratio and the Strength of Soil-Cement Mixtures." Civil Engineering and Public Works Review. Vol.55, No. 64B July 1960 (London) p. 903.

[2]Harris, F.A., "Selection and Design of Semi-Flexible and Conventional Type Pavements." Highway Research Board Proceedings. Vol. 35, 1956, p. 117.

specimens of soil-cement. In soil-cement, however, the hydrating cement will not only pick up loose water from the porous gel, but it will also probably attract water from the pockets of trapped soil, thus resulting in more shrinkage.

Whereas the water content in concrete is the largest single factor influencing shrinkage, the importance of water content in soil-cement depends upon the soil type. Water content has a more significant effect on soil-cements produced from fine grained soils than it does on soil-cements produced from coarse soils.

The most valuable analogy of soil-cement shrinkage with concrete shrinkage can be drawn on the basis of the effect of the type and the gradation of the aggregate. In concrete the ability of the aggregate to resist the shrinkage of the paste depends largely upon the compressibility of the aggregate and the volume change as it dries. By using a direct analogy, the following possible explanation of shrinkage in soil-cement can be given.

A POSSIBLE EXPLANATION OF SHRINKAGE IN SOIL-CEMENT

Miles D. Catton has described the structure of soil-cement as pockets of trapped soil linked together by agglomerations of cement grains and soil grains.[1] This

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[1]Catton, M.D.,"Research on the Physical Relations of Soil and Soil-Cement Mixtures." Proceedings, Highway Research Board. Vol. 20, (1940) p. 854.

concept of structure is most important in developing the theory here presented for a possible explanation for shrinkage in soil-cement.

The agglomerations to which Catton refers, consist of cement grains which have picked up a number of soil grains; the number of soil grains depends upon the soil grain size. When a small amount of cement has been added to a fine grained soil, a number of these agglomerations are formed throughout the soil. This accounts for the change in soil properties and grain size distribution due to the addition of a small amount of cement.[2,3] A soil which is so treated is known as a cement modified soil. When enough cement has been added to link all the agglomerations together with pockets of trapped soil, the mixture is known as soil-cement. In other words, in soil-cement, pockets of soil are linked together by a honeycomb structure of agglomerations: the linked agglomerations provide the rigidity of the structure.

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[2] "Laboratory Investigation of Soil-Cement Mixtures For Subgrade Treatment in Kansas." Proceedings, Highway Research Board. Vol. 17, Pt.II, (1937) p. 93.

[3] Reid, C.R., " Concrete Pavement Subgrade Design, Construction, Control" and E.J. Simpson and H.G. Henderson, "Dispersion of Soils and Soil-Cement Mixtures," Proceedings, Highway Research Board, Vol. 19, (1939) p. 541 and 551.

The pockets of trapped soil in a fine grained soil-cement structure can be considered analagous to the aggregate particles in concrete. The agglomerations can be thought of as cement paste which has been adulterated by the intrusion of minute soil particles. As the soil grains increase in size, the quantity picked up by the cement becomes less and less until, if there are only a few small grains, the cement paste becomes fairly homogenous.

It appears that the basic difference between soil-cements of different soil grain size, lies in the degree of homogeneity of the cement paste and the composition of that part of the structure which corresponds to the aggregate in concrete.

A possible explanation for shrinkage in soil-cements can be given by extending Catton's concept of the structure of soil-cement to include soils of coarser grain size, and by considering Carlson's contention that different shrinkage in different concrete aggregates is accounted for by the difference in compressibility of the aggregate.[4]

In concrete, the compressive force on the aggregate is caused by the shrinking cement paste. In soil-cement the shrinkage of the paste (and, therefore, the compressive

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[4]Carlson. Loc Cit.

force) will probably be somewhat less, since the tensile strength of the paste has probably been lessened by the presence of minute soil particles. However, the resistance to shrinking which is supplied by the pockets of trapped soil will be so much less than that of solid aggregate particles that the pockets of soil should be readily compressed.

If the grain size of the soil is increased so that the pockets of trapped soil are partially replaced by solid sand particles, shrinkage should be much less. Similarly if there is a complete absence of fines so that the paste is fairly homogenous and coats the larger size soil particles, in a manner similar to that encountered in concrete, shrinkage should still be less because the individual sand particles are so much more resistant to compressive forces than are the soil-pockets.

It would, therefore, appear that the amount of shrinkage which takes place in different soil-cements primarily depends upon the following factors:

(1) The proportion of the pockets of trapped soil to the number of individual soil particles contained in the structure.

(2) The shrinkage of the pockets of trapped soil and individual particles due to moisture losses.

(3) The compressive force of the shrinking cement

paste on the pockets of trapped soil and on the individual particles.

(4) The homogeneity of the cement paste.

Considering these factors, it is possible to explain the trends which were evident in the laboratory testing programme. These are best explained by considering each variable which was investigated separately for each soil.

A. Increasing Cement Content. In a fine grained soil such as that of the Caywood pit, increasing cement content would probably increase the number of agglomerations which were formed. The pockets of trapped soil would, therefore, be smaller but there would be more of them. The compressive force resulting from the increase in the agglomerations should be greater. As a result the Caywood soil should shrink more with increasing cement but the increased shrinkage should not be abrupt, since the quality of the paste is not much improved.

With a soil similar to the Hennig pit material, increased cement content should have a more significant effect. This would be because fewer soil fines are available to adulterate the cement. Thus, increasing cement content instead of forming more agglomerations, improves the quality of the paste resulting in more compressive force on the existing soil pockets. This is probably why the soil-cement of the Hennig pit showed a sharper increase in shrinkage

with increased cement content than did the soil-cement of the Caywood pit.

The soil from the Shepert pit was very coarse and possessed few fines. Thus, when mixed with cement, it is probably more like a concrete than a soil-cement. Therefore, increasing cement content at a constant water content should have an effect similar to that of concrete: very little, if any, increased shrinkage due to the lowering of the water/cement ratio.

B. Increasing Initial Moisture Content. The effect of moisture content on the quality of the soil-cement appears to arise from its influence on compaction rather than its relation to cement content. If a soil-cement is kept at a constant dry density, with increasing moisture content, more water must be absorbed and adsorbed by the soil particles and voids. Therefore, when the soil-cement specimen dries, it should show increased shrinkage due to an increase in moisture content. Moreover, the shrinkage should be greater for finer grained soils since these soils will take up water more readily. This was true for the Caywood and Hennig soil-cements. It was especially so for the Caywood soil-cement at moisture contents above optimum. According to the theory that the Shepert soil-cement acts more like a concrete, it should have shown an increase in shrinkage with increased moisture content. The fact that it

did not could possibly be explained because the cement paste between the particles cracked upon shrinking. This has been observed in concrete shrinkage where the cement paste cracked between large size particles.[5]

C. Increasing Dry Density. Increasing the dry density of a soil-cement at a constant cement and moisture content should decrease shrinkage because of more grain to grain contacts. The soil would then have greater resistance to the compressive force of the shrinking cement paste. This was apparently what happened with the soil-cements from the Hennig and Shepert material. There is no readily explainable reason for the fact that the Caywood material showed an increase in shrinkage with an increase in dry density.

D. The Effect of Curing Conditions. Curing conditions affect the shrinkage in soil-cement inasmuch as they affect the stability of the cement paste. For the most ideal condition, that of the sealed specimens, shrinkage is less because the paste is more stable and resistant to shrinkage forces resulting from drying.

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[5]See Chapter III, " The Effect of Type and Gradation of Aggregate."

CHAPTER VII

FIELD OBSERVATIONS

GENERAL PROGRAMME

The field programme carried out in connection with the study of shrinkage cracking in soil-cement, consisted of observations on two soil-cement projects. The two projects were: (1) eleven miles of soil-cement base course between Hay Lake and New Sarepta on Highway 21 and, (2) thirteen miles of soil-cement base course between Spruce Grove and Carvel Corner on Highway 16. The soil-cement was mixed at a central plant for each project. Spreading, compacting and shaping was carried out in a manner similar to that previously described by Domaschuk.[1]

The main purpose of the field programme was to obtain qualitative data on the formation and frequency of shrinkage cracks, in order to ascertain whether or not trends evident from the laboratory testing programme were reflected in the field construction.

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[1]Domaschuk. Op. Cit. p. 112-118.

FORMATION OF SHRINKAGE CRACKS

The shrinkage cracks in soil-cement base courses showed some signs of development two days after the material had been shaped and compacted. The actual time of development depends primarily upon: (1) the temperature and humidity, (2) the time between final compaction and the application of the seal coat, (3) the nature of the seal coat, (4) the subgrade moisture content and (5) the moisture content of the soil-cement.

In many cases it was difficult to determine the time of development of the shrinkage cracks. If the seal coat was particularly heavy, the cracks could not be discerned until the seal lost its tackiness and the cracks were well developed. This would usually take about seven days. If the temperature was comparatively low during the curing period and the relative humidity was high, it would take about four days for the cracks to develop. The minimum time ever observed for cracks to form was two days after final compaction.

The surveys of shrinkage cracking were usually carried out at least three weeks after the soil-cement was spread. Spot checks, taken at various points along the projects, indicated that, after about a week in place, the cracking was fully developed.

A similar pattern of cracking was formed on both soil-cement projects which were examined. Both longitudinal and transverse cracking occurred. The transverse cracks occurred at intervals which varied in length. There did not appear to be any relation between the width of the crack and the length of the interval. The longitudinal cracks were usually formed along the construction joint formed by adjacent lanes. On both projects the total width of the pavement was made up of four lanes. At each construction joint there usually occurred a longitudinal crack. In some cases, longitudinal cracking occurred a few feet in from the outside edge of the shoulders. In some cases these cracks occurred during compaction. Since the outside edge had no lateral support and was on a slight slope, it tended to slip down the slope under the load of the heavy compacting plant. To avoid this, the outside of the shoulder was compacted much less than the interior of the base course.

The three most significant observations concerning the formation of shrinkage cracks in the field were as follows:

(1) All shrinkage cracks extend to the full depth of the pavement.

(2) There appears to be no relationship between the width of the cracks and the distance between the cracks.

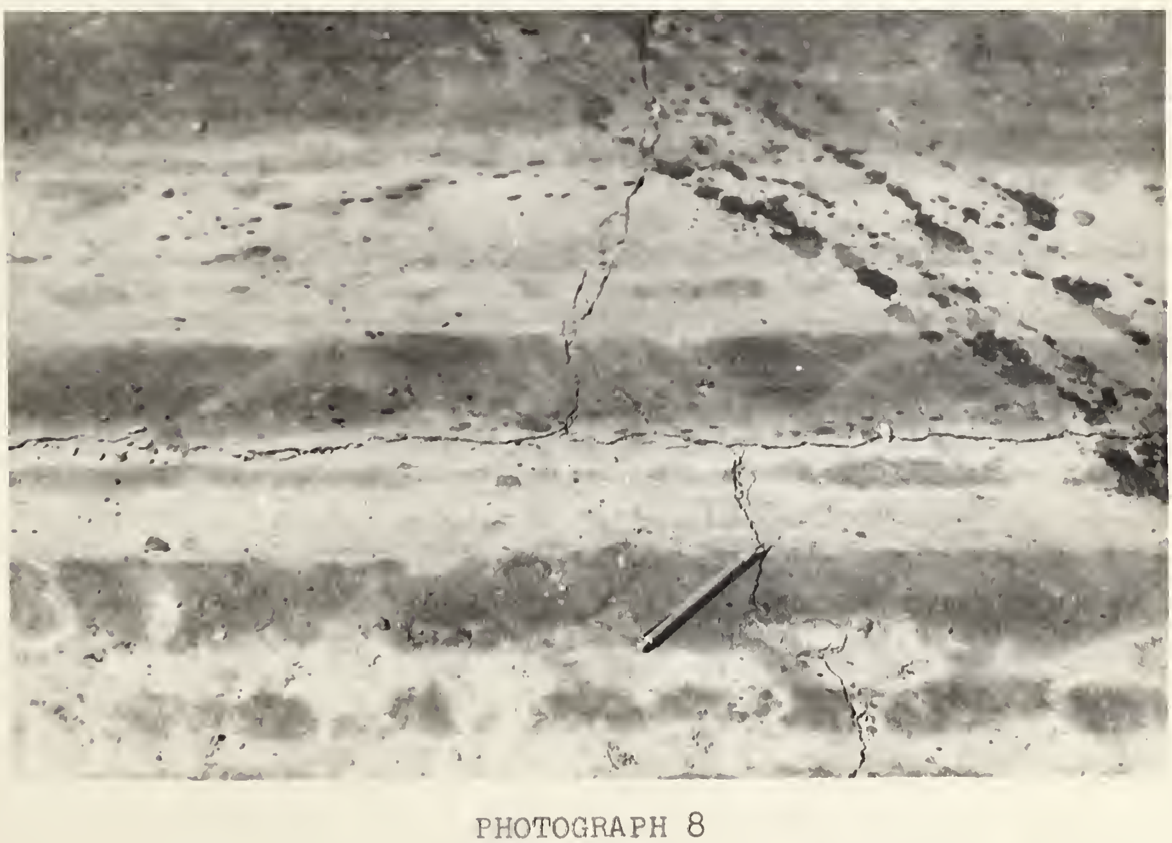
(3) Transverse cracks in practically all cases

extend across the entire width of the pavement. This is true even when the lanes may have been laid several days apart.

Photographs 7 and 8 show typical cracks as they occur in the soil-cement base courses. Photograph 7 is a single transverse crack. Photograph 8 shows a transverse crack extending across two lanes and a longitudinal crack along the construction joint between lanes.

PHOTOGRAPH 7

Transverse Shrinkage Crack.



PHOTOGRAPH 8

Longitudinal and Transverse Shrinkage Cracks.

MEASUREMENT OF SHRINKAGE CRACKING

With the methods at hand, the measurement of the actual width of cracks proved to be impossible at the time the field observations were made. On the surface, the cracks are usually spalled and very irregular as shown in photographs 7 and 8. Very often the cracks extended obliquely down through the pavement and appeared to vary in width throughout the depth. Furthermore, it is very likely that the crack opening changes in width with changes in temperature and humidity throughout the day. To obtain an accurate measurement of the crack openings would require special instrumentation and continual observations. Both of these requirements were beyond the scope of this study.

It was, therefore, decided to measure the distance between the cracks as they occurred in the base course. This was done by using a Rollotape, which was simply a wheel similar to that of a bicycle, which recorded distance in feet. The distance between cracks was measured for each fifty foot section of the base course which was investigated. This provided data which could be used to relocate cracks after the roadmix was applied, if this was required, and allowed a tabulation of crack frequency.

CRACK FREQUENCY

It was decided that the best method of tabulating the data on field shrinkage cracks was by recording the total number of transverse cracks in each consecutive fifty foot section. This gives an indication of the crack spacing and shows the different frequency encountered throughout the length of the soil-cement base course.

Plate 22 is a shrinkage crack frequency chart for the soil-cement base course between Hay Lakes and New Sarepta on Highway 21. This entire chart was prepared on the basis of the total number of cracks for each fifty foot section. Approximately nine miles of this project were surveyed. The results of this survey indicate that there are many fluctuations in shrinkage crack frequency throughout the length of the project. The first mile is the worst section with respect to shrinkage cracking. There appears to be less cracking in the soil-cement produced from the Ertman pit than that produced from the Wagner pit. Unfortunately, at the time of writing, there was no data available from the project to investigate the effect of variations as recorded in the control data. Furthermore, the soils used for this project were not subjected to shrinkage investigations in the laboratory project. Plate 22, therefore, serves little but to give an indication of a

typical shrinkage frequency distribution for a field project.

Plate 23 is a crack frequency chart for the soil-cement base course between Spruce Grove and Edmonton Beach Corner on Highway 16. At the time of writing, this was the extent of the finished portion of this project. From station 730 + 00 to station 830 + 00 was surveyed on the basis of the most frequent interval occurring within each one-hundred foot station. Thus, if the most frequent interval was ten feet, a total of ten cracks were plotted on the frequency chart. This method was less accurate than the method of counting and measuring the cracks for each fifty foot section as was done for the remainder of the survey. These results show that there is a notable variation in crack frequency between the two soils which were used and also within the length covered by each soil. There was generally less cracking in the soil-cement produced from the McGinn pit material than that of the Hennig pit.

When the field programme was initiated, it was felt that the Highway 16 project would prove to be the most valuable for shrinkage investigation purposes, since it was planned to use the material from the Hennig pit and that from the Caywood pit within a relatively short distance. Due to a shortage of material which

was discovered after the Caywood pit was opened, this material was not used. As a result, the comparison between the field shrinkage characteristics of these two soils could not be made.

The field control data from this project was obtained on a regular random sampling basis. This proved adequate for quality control. Since there are so many variations in shrinkage crack frequency within a relatively short distance, the data is insufficient to relate with shrinkage cracking.

FACTORS AFFECTING SHRINKAGE CRACKING IN THE FIELD

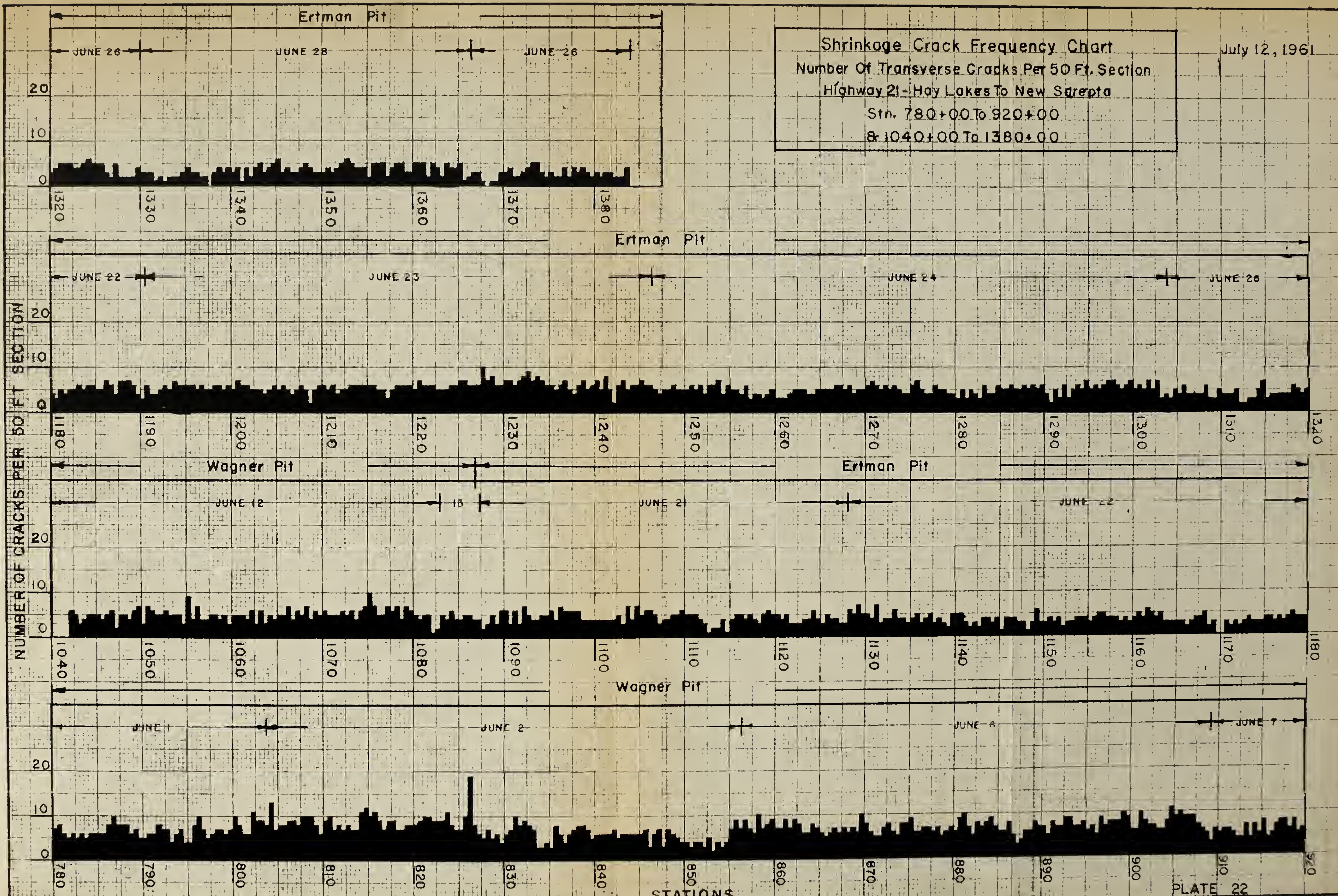
In the laboratory testing programme, specimens were prepared and cured under conditions which were relatively stable. These conditions do not exist in the field. The variations in climate throughout the duration of the project probably has a marked influence upon the rate of development and the amount of shrinkage cracking. Another variable factor, which probably influences the rate and amount of drying shrinkage, is the moisture conditions of the subgrade. If the subgrade is dry when the soil-cement is spread, it would tend to absorb water from the mix. Usually the subgrade was sprayed before the base course was placed but it was not a well controlled process. Because of the effect of climate and subgrade

moisture conditions, it is difficult to say what part of the field shrinkage corresponds to the shrinkage developed in the laboratory specimens.

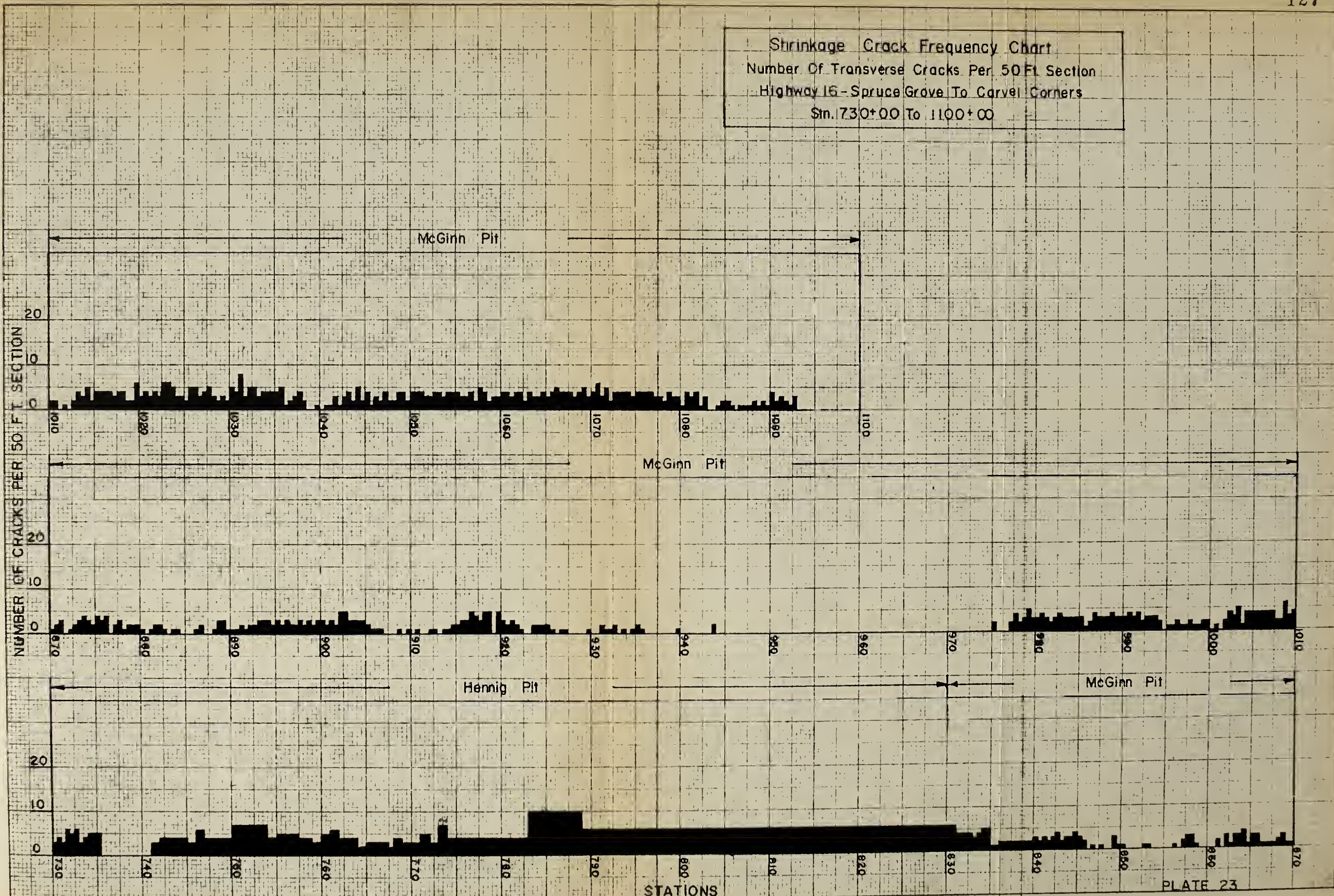
The most notable feature, which was observed in the field survey, was that the quality of the seal coat appeared to have a significant influence on the amount of shrinkage. More shrinkage occurred in areas where the seal coat was poor or where it penetrated the surface, than in areas where a good non-penetrating membrane was formed. This was particularly evident on Highway 16. On this project the quality of the seal coat varied considerably. The quality of the seal appeared to be the most important factor in accounting for different frequencies in shrinkage which occurred in the base course.

In discussing the formation of shrinkage cracks, it was pointed out that practically all the cracks extended across the full width of the base course, in spite of the fact that several days may have lapsed between the construction of adjacent lanes. In some cases the cracks were slightly offset as shown in Photograph 8; however, they can still be considered as extensions of one crack, since the offset distance is usually quite small. It is unlikely that the adjacent lanes of soil-cement had the same physical properties or that climatic conditions remained the same. Variations in cement content and initial

moisture content of up to two percent are not uncommon for even a single day's production. In addition it was noted that the quality of the seal coat often varied between adjacent lanes. These facts would lead one to believe that the adjacent lanes would not necessarily shrink the same amount. Since the shrinkage cracks do occur at the same interval for adjacent lanes, the pattern of cracking must be determined by the shrinkage characteristics of the first lane. When a lane of soil-cement is laid abutting a lane which has already formed its own shrinkage cracks, it will be subjected to a certain amount of stress from the differential movement within the first lane. Since the fresh soil-cement will be tending to shrink either more or less after is has been placed, it will be influenced by the differential movement of the adjacent lane to form cracks at the point of maximum stress. This will be at the same point as the cracks on the first lane, since it is at these cracks that the maximum differential movement will occur. Because the cracking pattern for the full width of the highway is determined by the first lane, a reduction in the factors tending to produce shrinkage in the adjacent lanes, will be to no avail.



Shrinkage Crack Frequency Chart
Number Of Transverse Cracks Per 50 Ft. Section
Highway 21 - Hay Lakes To New Sarepta
Stn. 780+00 To 920+00
& 1040+00 To 1380+00
July 12, 1961
Ertman Pit
Wagner Pit
NUMBER OF CRACKS PER 50 FT SECTION
STATIONS
PLATE 22



Shrinkage Crack Frequency Chart
Number Of Transverse Cracks Per 50 Ft Section
Highway 16 - Spruce Grove To Carvel Corners
Stn. 730+00 To 1100+00
McGinn Pit
Hennig Pit
NUMBER OF CRACKS PER 50 F.T. SECTION
STATIONS
0
10
20
1010
1020
1030
1040
1050
1060
1070
1080
1090
1100
870
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860
PLATE 23

FIELD TRENDS IN SOIL-CEMENT SHRINKAGE COMPARED TO LABORATORY TRENDS

Due to a dearth of field data at the time of writing, it is impossible to compare shrinkage as measured in the laboratory with shrinkage as observed in the field, other than for the observed curing conditions. In the laboratory it was found that specimens which were sealed usually shrank less than specimens under other conditions of curing. It was similarly observed in the field that less shrinkage occurred in areas where the seal coat formed a skin-like membrane than in areas where the seal penetrated the soil-cement or was splotchy.

Even in areas where a good seal was obtained, there was often a notable variation in crack frequency. This could possibly be explained on the basis of moisture content, cement content or density, had sufficient data been available. Since it was not, these observations cannot be explained.

CONCLUSIONS FROM FIELD OBSERVATIONS

(1) The quality of the seal coat has an important effect on the amount of shrinkage which occurs in soil-cement base courses. The least shrinkage occurs where the seal coat forms a membrane which does not penetrate the soil-cement.

(2) When a soil-cement base course is constructed by using a conventional type spreader, the shrinkage pattern for the full width of the highway will be determined by the shrinkage characteristics of the first lane constructed.

(3) A full study of shrinkage in soil-cement field projects will require an intensified investigation of variations in the finished soil-cement. Normal field control data is insufficient to explain different frequencies in shrinkage in relatively short lengths of pavement.

CHAPTER VIII

RECOMMENDATIONS FOR FURTHER STUDY

On the basis of the results of the study of shrinkage in soil-cement, it is recommended:

(1). That further laboratory investigations be made of shrinkage in soil-cement, particularly to investigate the relationship between grain size and shrinkage. A variety of soils covering a wide grading range would be required for this investigation. Careful consideration should be given to the controlled laboratory environment to which the specimens are subjected, in order to give a good representation of the field conditions. It is likely that at least a year would be required for the specimens to reach equilibrium with respect to shrinkage.

(2). That a laboratory investigation be carried out to determine the best curing aid to reduce shrinkage in soil-cement. Since the cement content and the initial moisture content are usually dictated by strength, durability and compaction requirements, the condition of curing appears to be the most likely variable which can be manipulated to control shrinkage.

(3). That a field investigation be carried out to quantitatively determine the extent of shrinkage cracking and the effect of normal variations in cement and moisture

content which occur in central plant mix production. This study would require intensified investigations on the variable factors in soil-cement for several test sections on several soil-cement projects. Special instrumentation would be required to measure crack widths and to determine the fluctuations in width due to changes in temperature, and humidity. The electrical conductivity method of measuring cement content and nuclear equipment for measuring inplacedensity and moisture content, could be used to good advantage for this investigation. These apparati are available to the Alberta Research Council.

(4). Than an investigation of the effect of trace chemical additives in reducing shrinkage in soil-cement be made. It is a well-known fact that there are many chemicals which can economically be added in trace quantities to soil-cement to improve strength and durability.[1] The most promising aspect of these additives is the fact that the cement content can be reduced while maintaining strength and durability requirements. Unless the trace chemicals themselves introduce a shrinkage factor, reducing the cement content should reduce shrinkage.

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[1]Lambe, T.W., Zu-Cheigh Moh,"Improvement of Strength of Soil-Cement With Additives,"Highway Research Board Bulletin 183, (1955) and Lambe, T.W., Michaels,A.B., Zu-Cheigh Moh, "Improvement of Soil-Cement With Alkali Metal Compounds." Highway Research Board Bulletin 241,(1960).

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APPENDIX A

Data Sheets for Physical Properties of Sands.

<u>Caywood Pit</u>

Specific Gravity

Grain Size Analysis

Standard Proctor Compaction

<u>Hennig Pit</u>

Specific Gravity

Grain Size Analysis

<u>Shepert Pit</u>

Specific Gravity

Grain Size Analysis

Standard Proctor Compaction

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SOIL MECHANICS LABORATORY

SPECIFIC GRAVITY

PROJECT: THESIS - SOIL-CEMENT
SITE: CAYWOOD PIT
SAMPLE: FINE SAND
LOCATION: HWY 16 - WEST
HOLE: DEPTH:
TECHNICIAN: J. I. C. DATE: AUG 1

Sample No.	1	2
Flask No.	103	111
Method of Air Removal	HEAT + VACUUM	HEAT + VACUUM
W_{b+w+s}	775.11	768.25
Temperature T	24.7°	25.2
W_{b+w}	682.55	676.00
Evaporating Dish No.	3	4
Wt. Sample Dry + Dish	190.46	190.48
Tare Dish	43.40	43.35
W_s	147.06	147.13
G_s	2.70	2.68

W_{b+w+s} = Weight of flask + water + sample at T°.
W_{b+w} = Weight of flask + water at T° (flask calibration curve).
W_s = Weight of dry soil
G_s = Specific gravity of soil particles $= \dfrac{W_s}{W_s + W_{b+w} - W_{b+w+s}}$

Determination of W_s from wet soil sample:

Sample No.			Sample No.		
Container No.			Container No.		
Wt. Sample Wet + Tare			Wt. Test Sample Wet + Tare		
Wt. Sample Dry + Tare			Tare Container		
Wt. Water			Wt. Test Sample Wet		
Tare Container			W_s		
Wt. of Dry Soil					
Moisture Content w %					

Description of Sample: VERY FINE GREYISH-BROWN SAND - 52% PASSING #200 - AIR DRIED

Remarks:

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SOIL MECHANICS LABORATORY

SIEVE ANALYSIS

PROJECT THESIS
SITE HWY 16 - WEST
SAMPLE FINE SAND
LOCATION CAYWOOD PIT
HOLE DEPTH
TECHNICIAN J.C. DATE AUG 2

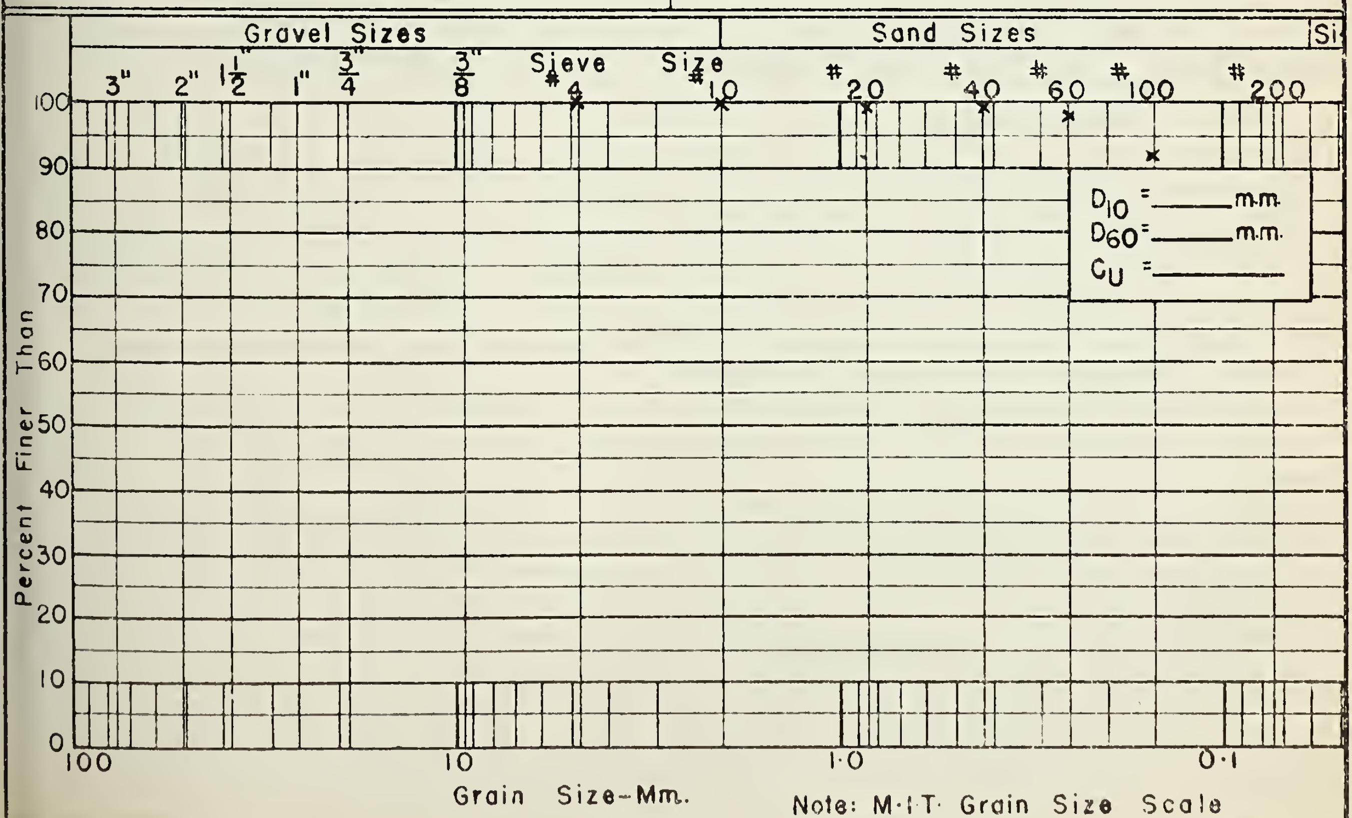
Total Dry Weight of Sample ______	Sieve No.	Size of Opening Inches	Size of Opening Mm.	Weight Retained gms.	Total Wt. Finer Than gms.	Percent Finer Than	% Finer Than Basis Orig. Sample
Initial Dry Weight Retained No. 4							
Tare No. ______							
Wt. Dry + Tare ______							
Tare ______		3/4	19·10				
Wt. Dry ______		3/8	9·52				
	4	·185	4·76	0	500.0	100.0	
Passing	4						
Initial Dry Weight Passing No. 4	10	·079	2·000	0	500.0	100.0	
Tare No. ______	20	·0331	·840	1.1	498.9	99.7	
Wt. Dry + Tare ______	40	·0165	·420	2.1	496.8	99.5	
Tare ______	60	·0097	·250	11.0	485.8	97.3	
Wt. Dry ______	100	·0059	·149	22.4	463.4	92.5	
	200	·0029	·074	166.7	296.7	59.4	
Passing	200						

Description of Sample FINE BROWNISH SILTY SAND.

Time of Sieving 10 MIN.

Method of Preparation SAMPLE WAS AIR DRIED - MATERIAL RETAINED ON 200 MESH SIEVE WAS WASHED

Remarks COMBINED ANALYSIS - 50g TAKEN FROM PAN FOR HYDROMETER ANALYSIS.



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SOIL MECHANICS LABORATORY
HYDROMETER TEST

PROJECT Thesis - Soil Cement
SITE Caywood Pit
SAMPLE Fine Sand
LOCATION Hwy 16 - West
HOLE DEPTH
TECHNICIAN J.I.C. DATE July 26

Date	Temp.	Time	Elapsed Time	R'_h	$R_h = R'_h + c_m$	D m.m.	$R_h + m_t - c_d$	W.%	W % Basis Orig. Sample	Remarks
July 26/61	24.5	1415	–	–	–	–	–	–	–	–
	"		1/4	28.4	28.9	.092	29.8	99.8	59.2	
	"		1/2	26.9	27.4	.066	28.3	94.7	56.2	
	"		1	23.2	23.7	.049	24.6	82.5	49.0	
	"		2	17.5	18.0	.037	18.9	63.3	37.5	
	"	1420	2	17.4	17.9	.036	18.8	63.0	37.4	
	"		4	11.5	12.0	.027	12.9	43.2	25.6	
	24.0		8	7.4	7.9	.020	8.7	29.2	17.3	
	"		15	5.5	6.0	.015	6.8	22.8	13.5	
	"		30	4.0	4.5	.011	5.3	17.8	10.6	
	"	1518	1 Hr.	3.1	3.6	.0076	4.4	14.7	8.7	
	23.5		2 Hr	2.5	3.0	.0054	3.7	12.4	7.4	
	22.7	1930	5 Hr - 12 M	2.0	2.5	.0034	3.0	10.1	6.0	
	"	2118	7	1.6	2.1	.0029	2.6	8.7	5.1	
July 27	22	0818	18	1.5	2.0	.0018	2.4	8.1	4.8	

Hydrometer No.s 9850 and ______ Graduate No. ______

$W\% = \frac{100}{W_s} \cdot \frac{S_s}{S_s - 1}(R_h + m_t - c_d) = 3.350\ (R_h + m_t - c_d)$

Meniscus correction = c_m = 0.5 and ______ respectively

Dispersing agent used None Amount –

Correction for change in density of liquid due to addition of dispersing agent = c_d

c_d = 0 and – respectively

Specific Gravity of Solids = G_s 2.69

Description of Sample
Light Brown Fine Silty Sand

Method of Preparation Combined Analysis - Sample Air Dried - Mechanically Dispersed

Remarks First four readings were repeated until constant

Initial Moisture Content

Container No. ______
Wt. Sample Wet + Tare ______
Wt. Sample Dry + Tare ______
Wt. Water ______
Tare Container ______
Wt. of Dry Soil ______
Initial Moisture w % ______

Dry Weight of Sample

Container No. 1
Wt. Sample (~~Wet~~/Dry) + Tare 1089.3
Tare 1041.8
Wt. (~~Wet~~/Dry) Soil 47.5
Dry Weight from Initial Moisture = $\frac{100 \times \text{Wt. Wet Soil}}{100 + \text{Init. Moist. \%}}$ = ______

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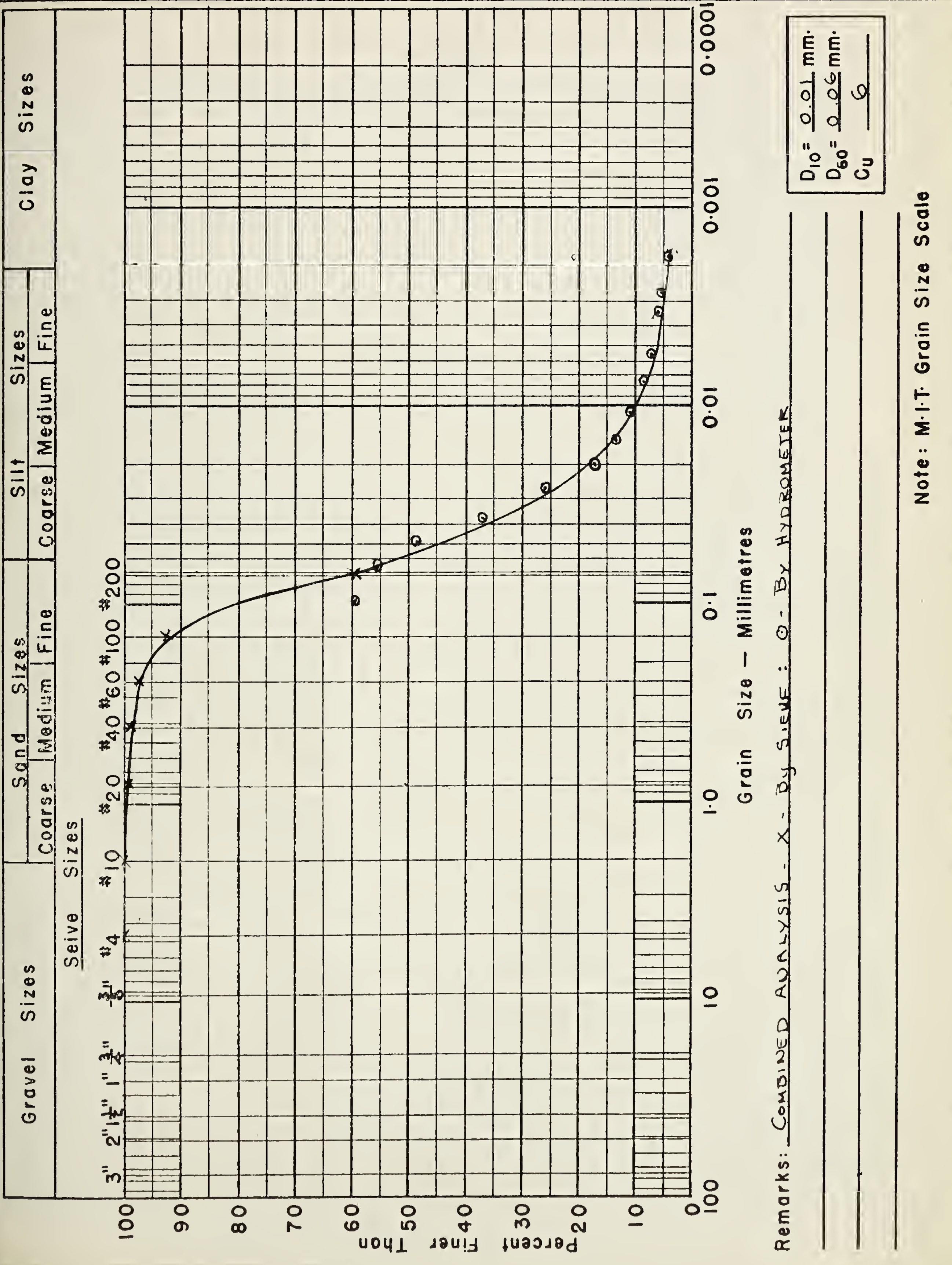
SOIL MECHANICS LABORATORY
GRAIN SIZE CURVE

PROJECT	THESIS. – SOIL CEMENT		
SITE	HIGHWAY 16 - WEST		
SAMPLE	FINE SAND		
LOCATION	CAYWOOD PIT		
HOLE		DEPTH	
TECHNICIAN	J.C.	DATE	AUG. 3



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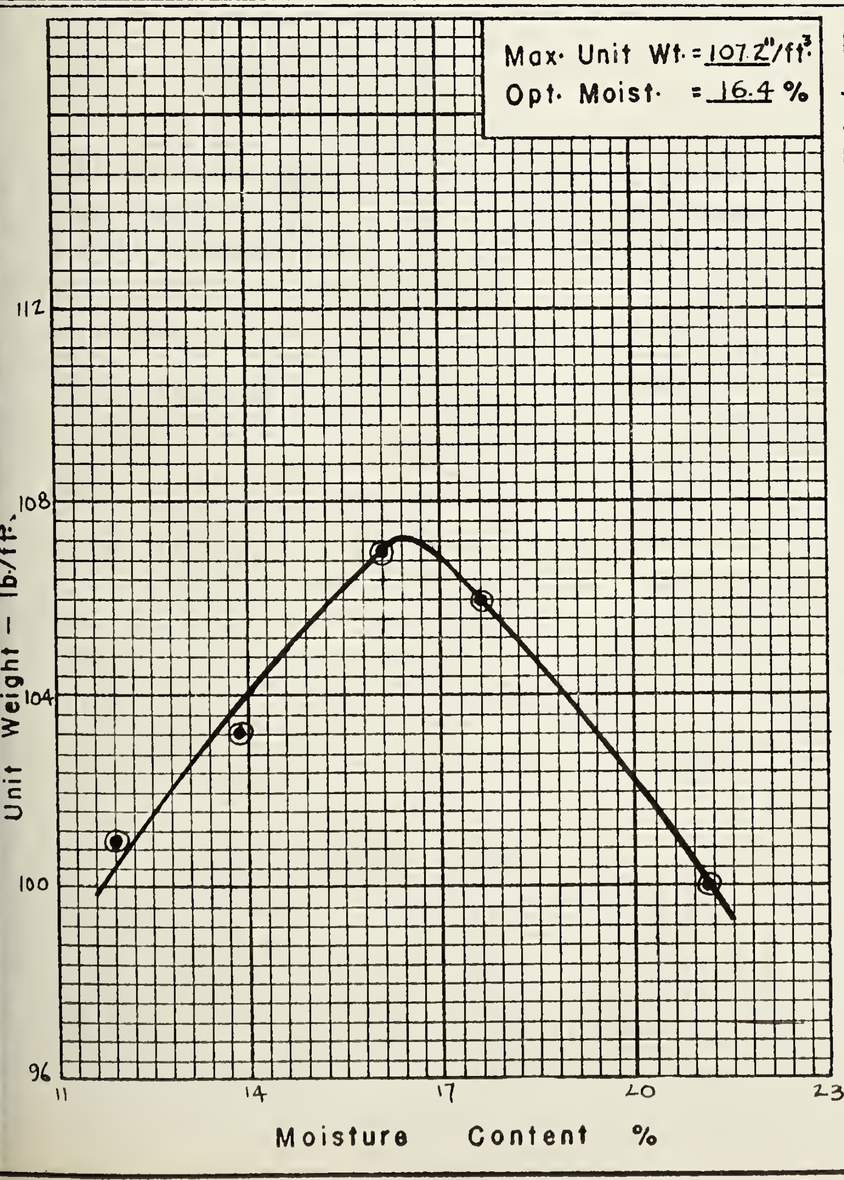
SOIL MECHANICS LABORATORY
COMPACTION TEST

PROJECT	THESIS - SOIL CEMENT
SITE	CAYWOOD PIT
SAMPLE	FINE SAND
LOCATION	HIGHWAY 16 WEST
HOLE	DEPTH
TECHNICIAN J.C.	DATE AUG 2

	Trial Number		1	2	3	4	5	
Unit Weight Determination	Mold No.		5	5	5	5	5	
	Wt. Sample Wet + Mold		3773.4	3835.8	3947.5	3945.8	3901.6	
	Wt. Mold		2063.2	2063.2	2063.2	2063.2	2063.2	
	Wt. Sample Wet		1710.2	1772.6	1884.3	1882.6	1838.4	
	Volume Mold ft.^{3}		1/30	1/30	1/30	1/30	1/30	
	Wet Unit Weight lb./ft.^{3}		113.0	117.3	124.5	124.4	121.5	
	Dry Unit Weight lb./ft.^{3}		101.0	103.2	107.0	106.0	100.1	
Moisture Content Determination	Container No.		V81	V82	9	V52	V83	
	Wt. Sample Wet + Tare		133.968	120.948	154.645	164.488	175.605	
	Wt. Sample Dry + Tare		127.244	113.564	143.659	150.496	158.066	
	Wt. Water		6.724	7.384	10.986	13.992	17.539	
	Tare Container		70.488	60.165	75.836	71.341	75.380	
	Wt. Dry Soil		56.756	53.399	67.823	79.155	82.686	
	Moisture Content		11.88	13.81	16.20	17.64	21.20	



Method of Compaction STANDARD PROCTOR FIELD APPARATUS.

Diam. Mold 4"

Height Mold 4 18/32"

Volume Mold 1/30

No. of Layers 3

Blows per Layer 25

Ht. of Free Fall 12"

Wt. of Tamper 5 lb.

Shape of Tamping Face O

Description of Sample

Remarks

UNIVERSITY of ALBERTA DEP'T. of CIVIL ENGINEERING SOIL MECHANICS LABORATORY **SPECIFIC GRAVITY**	PROJECT THESIS - SOIL-CEMENT SITE HENNIG PIT SAMPLE SAND LOCATION HWY 16 - WEST HOLE DEPTH TECHNICIAN J.I.C. DATE AUG 3

Sample No.	1	2
Flask No.	103	111
Method of Air Removal	HEAT + VACUUM	HEAT + VACUUM
W_{b+w+s}	775.85	769.01
Temperature T	23.6°	24.3°
W_{b+w}	682.81	676.10
Evaporating Dish No.	5	6
Wt. Sample Dry + Dish	194.45	192.39
Tare Dish	45.64	43.50
W_s	148.81	148.89
G_s	2.67	2.66

W_{b+w+s} = Weight of flask + water + sample at T°.

W_{b+w} = Weight of flask + water at T° (flask calibration curve).

W_s = Weight of dry soil

G_s = Specific gravity of soil particles $= \dfrac{W_s}{W_s + W_{b+w} - W_{b+w+s}}$

Determination of W_s from wet soil sample:

Sample No.			Sample No.		
Container No.			Container No.		
Wt. Sample Wet + Tare			Wt. Test Sample Wet + Tare		
Wt. Sample Dry + Tare			Tare Container		
Wt. Water			Wt. Test Sample Wet		
Tare Container			W_s		
Wt. of Dry Soil					
Moisture Content w %					

Description of Sample: MEDIUM SAND - LIGHT BROWN - APPROX. 8% PASSING #200 - AIR DRIED

Remarks:

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SOIL MECHANICS LABORATORY

SIEVE ANALYSIS

PROJECT	THESIS
SITE	
SAMPLE	MEDIUM SAND
LOCATION	HENNIG PIT
HOLE	DEPTH
TECHNICIAN J.C.	DATE AUG 2

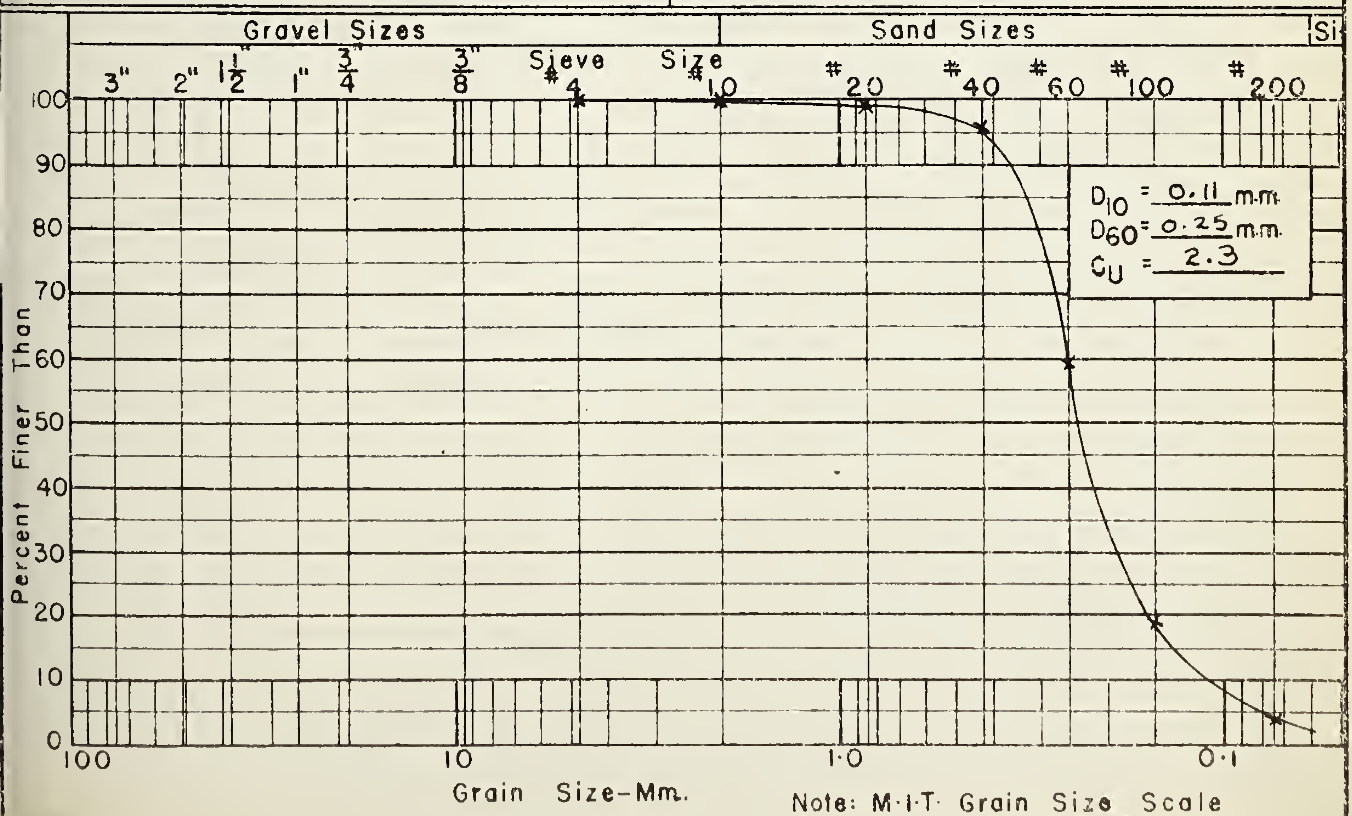
Total Dry Weight of Sample ______	Sieve No.	Size of Opening Inches	Size of Opening Mm.	Weight Retained gms.	Total Wt. Finer Than gms.	Percent Finer Than	% Finer Than Basis Orig. Sample
Initial Dry Weight Retained No. 4							
Tare No. ______							
Wt. Dry + Tare ______							
Tare ______		3/4	19·10				
Wt. Dry ______		3/8	9·52				
	4	·185	4·76	0	500.0	100.0	
Passing	4						
Initial Dry Weight							
Passing No. 4	10	·079	2·000	0	500.0	100.0	
Tare No. ______	20	·0331	·840	2.0	498.0	99.5	
Wt. Dry + Tare ______	40	·0165	·420	18.6	479.4	95.7	
Tare ______	60	·0097	·250	183.9	295.5	59.0	
Wt. Dry ______	100	·0059	·149	204.5	91.0	18.2	
	200	·0029	·074	73.5	17.5	3.5	
Passing	200			17.5			

Description of Sample: LIGHT BROWN MEDIUM SAND – NO ORGANIC MATERIAL.

Time of Sieving: 10 MIN.

Method of Preparation: SAMPLE WAS AIR DRIED

Remarks: ______



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SOIL MECHANICS LABORATORY

SPECIFIC GRAVITY

PROJECT	THESIS - SOIL CEMENT		
SITE	SHEPERT PIT		
SAMPLE	COARSE SAND		
LOCATION	HWY-		
HOLE		DEPTH	
TECHNICIAN	J.C.	DATE	AUG 1

Sample No.	1	2
Flask No.	103	111
Method of Air Removal	HEAT + VACUUM	HEAT + VACUUM
W_{b+w+s}	776.23	769.70
Temperature T	24.7°	23.5°
W_{b+w}	682.55	676.20
Evaporating Dish No.	1	2
Wt. Sample Dry + Dish	193.38	192.55
Tare Dish	43.67	42.83
W_s	149.71	149.72
G_s	2.67	2.66

W_{b+w+s} = Weight of flask + water + sample at T°.
W_{b+w} = Weight of flask + water at T° (flask calibration curve).
W_s = Weight of dry soil
G_s = Specific gravity of soil particles $= \dfrac{W_s}{W_s + W_{b+w} - W_{b+w+s}}$

Determination of W_s from wet soil sample:

Sample No.			Sample No.		
Container No.			Container No.		
Wt. Sample Wet + Tare			Wt. Test Sample Wet + Tare		
Wt. Sample Dry + Tare			Tare Container		
Wt. Water			Wt. Test Sample Wet		
Tare Container			W_s		
Wt. of Dry Soil					
Moisture Content w %					

Description of Sample: COARSE LIGHT BROWN SAND - FAIRLY UNIFORM ANGULAR PARTICLES.

Remarks:

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SOIL MECHANICS LABORATORY

SIEVE ANALYSIS

PROJECT Thesis - Soil Cement
SITE Shepert Pit
SAMPLE Coarse Sand
LOCATION Hwy
HOLE DEPTH
TECHNICIAN J.I.C. DATE Aug 2

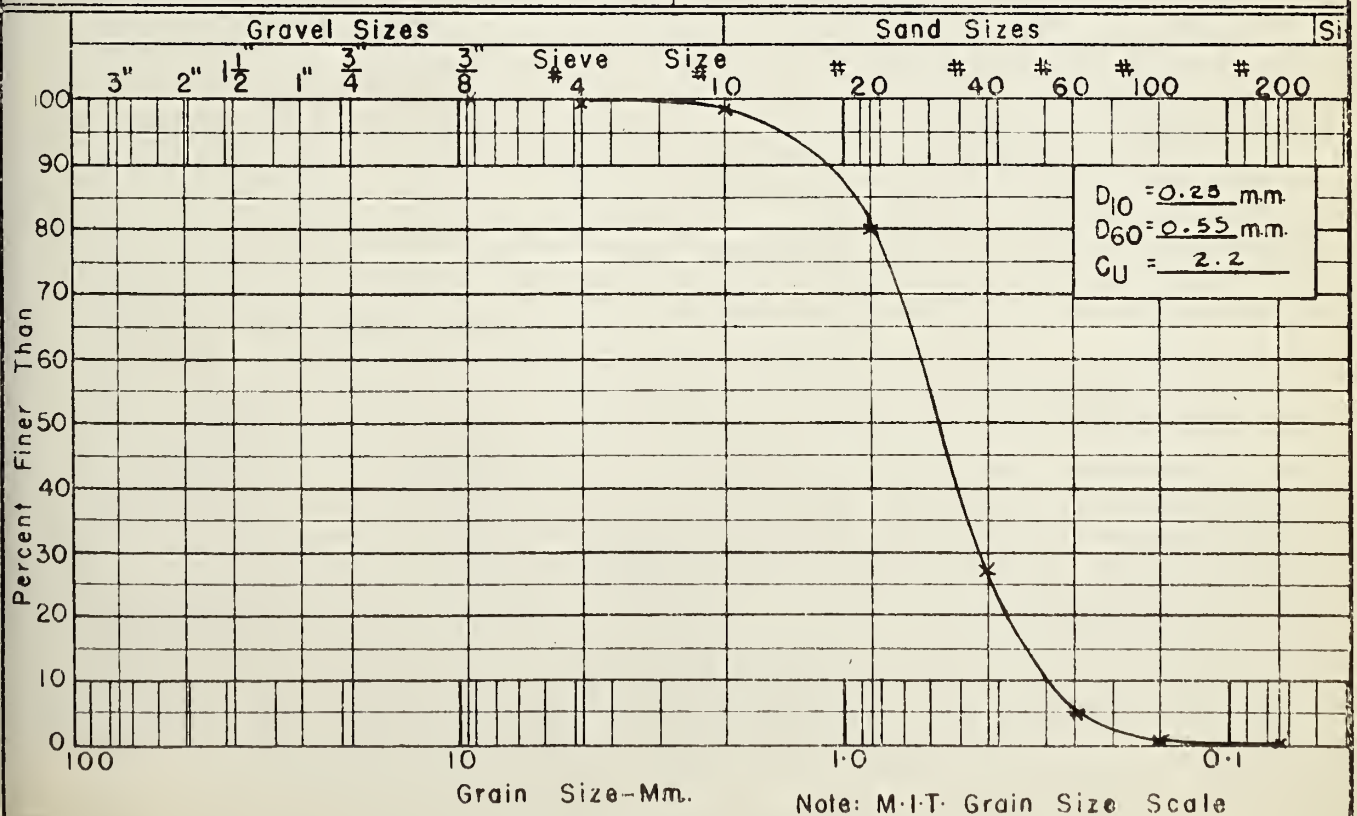
Total Dry Weight of Sample	Sieve No.	Size of Opening Inches	Size of Opening Mm.	Weight Retained gms.	Total Wt. Finer Than gms.	Percent Finer Than	% Finer Than Basis Orig. Sample
Initial Dry Weight Retained No. 4							
Tare No.							
Wt. Dry + Tare							
Tare		3/4	19·10				
Wt. Dry		3/8	9·52				
	4	·185	4·76	0	500.0	100.0	
Passing	4						
Initial Dry Weight Passing No·4	10	·079	2·000	5.0	495.0	99.00	
Tare No·	20	·0331	·840	95.1	399.9	80.00	
Wt· Dry + Tare	40	·0165	·420	264.1	135.8	27.20	
Tare	60	·0097	·250	111.1	24.7	4.90	
Wt· Dry	100	·0059	·149	20.2	4.5	0.90	
	200	·0029	·074	2.1	2.4	0.48	
Passing	200			2.4	0	0	

Description of Sample Coarse Light Brown Sand - Fairly Uniform - Angular Particles

Time of Sieving 10 min

Method of Preparation Sample Air Dried

Remarks



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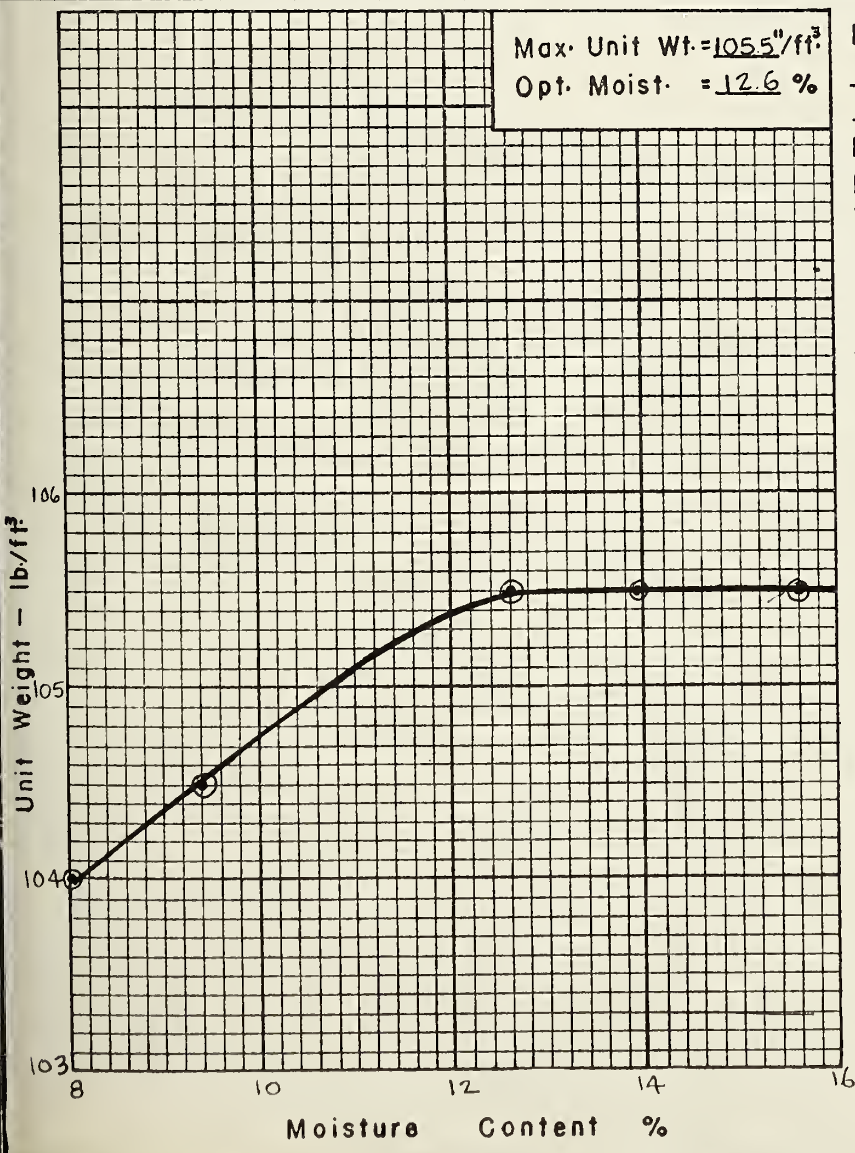
SOIL MECHANICS LABORATORY
COMPACTION TEST

PROJECT	THESIS - SOIL CEMENT
SITE	SHEPERT PIT
SAMPLE	COURSE SAND
LOCATION	HIGHWAY 16 WEST
HOLE	DEPTH
TECHNICIAN	H. ALTON DATE AUG. 2

	Trial Number		1	2	3	4	5	
Unit Weight Determination	Mold No.		S	S	S	S	S	
	Wt. Sample Wet + Mold		3760.0	3794.3	3857.8	3881.0	3904.1	
	Wt. Mold		2063.2	2063.2	2063.2	2063.2	2063.2	
	Wt. Sample Wet		1696.8	1731.1	1794.6	1817.8	1840.9	
	Volume Mold ft.^{3}		1/30	1/30	1/30	1/30	1/30	
	Wet Unit Weight lb./ft.^{3}		112.1	114.6	118.8	120.2	121.8	
	Dry Unit Weight lb./ft.^{3}		104.0	104.5	105.5	105.5	105.5	
Moisture Content Determination	Container No.		A3	A27	A28	A12	A17	
	Wt. Sample Wet + Tare		134.859	150.456	158.252	174.992	181.403	
	Wt. Sample Dry + Tare		129.268	142.816	148.260	161.868	166.477	
	Wt. Water		5.591	7.640	9.992	13.124	14.926	
	Tare Container		59.023	61.464	69.050	67.544	70.305	
	Wt. Dry Soil		70.245	81.352	79.210	94.324	96.172	
	Moisture Content		7.96	9.40	12.60	13.95	15.60	

Max. Unit Wt. = 105.5 #/ft.^{3}
Opt. Moist. = 12.6 %



Method of Compaction STANDARD PROCTOR FIELD APPARATUS.

Diam. Mold 4"

Height Mold 4 18/32"

Volume Mold 1/30

No. of Layers 3

Blows per Layer 25

Ht. of Free Fall 12"

Wt. of Tamper 5 lbs.

Shape of Tamping Face

Description of Sample COURSE LIGHT BROWN SAND - FAIRLY UNIFORM ANGULAR PARTICLES.

Remarks

APPENDIX B

Physical properties and Chemical analysis of cement.

Physical Properties of Cement.

Normal Consistency........................ 26%

Time of Set (Gillmore Test)

Initial........................ 4hrs. 15min.

Final........................ 6hrs.

Compressive Strength

1 day in moist air, 2days in water........ 1645 psi

1 day in moist air, 6 days in water....... 2947 psi

1 day in moist air, 27 days in water......4675 psi

Tensile Strength

1 day in moist air, 2 days in water....... 248 psi

1 day in moist air, 6 days in water....... 307 psi

CHEMICAL ANALYSIS OF CEMENT

(Carried out by Provincial Analyst)

Silicon dioxide - 22.07%

Aluminum oxide - 5.73%

Ferric oxide - 3.08%

Calcium oxide - 62.75%

Magnesium oxide - 3.25%

Sulfur trioxide - 1.98%

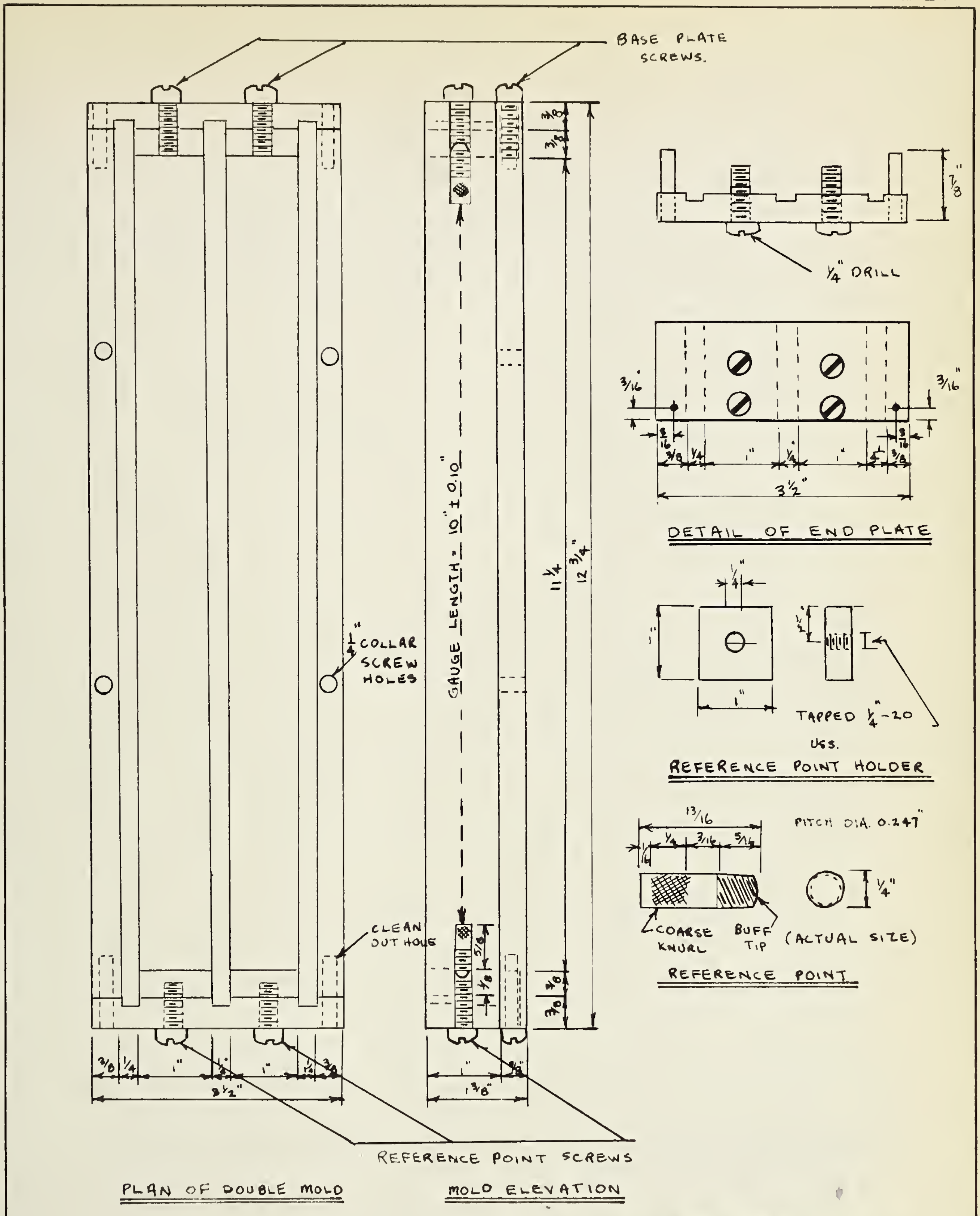
Loss on ignition- 1.58%

APPENDIX C

Working Drawing of Specimen Mold.

[illegible]

[illegible]



UNIVERSITY OF ALBERTA
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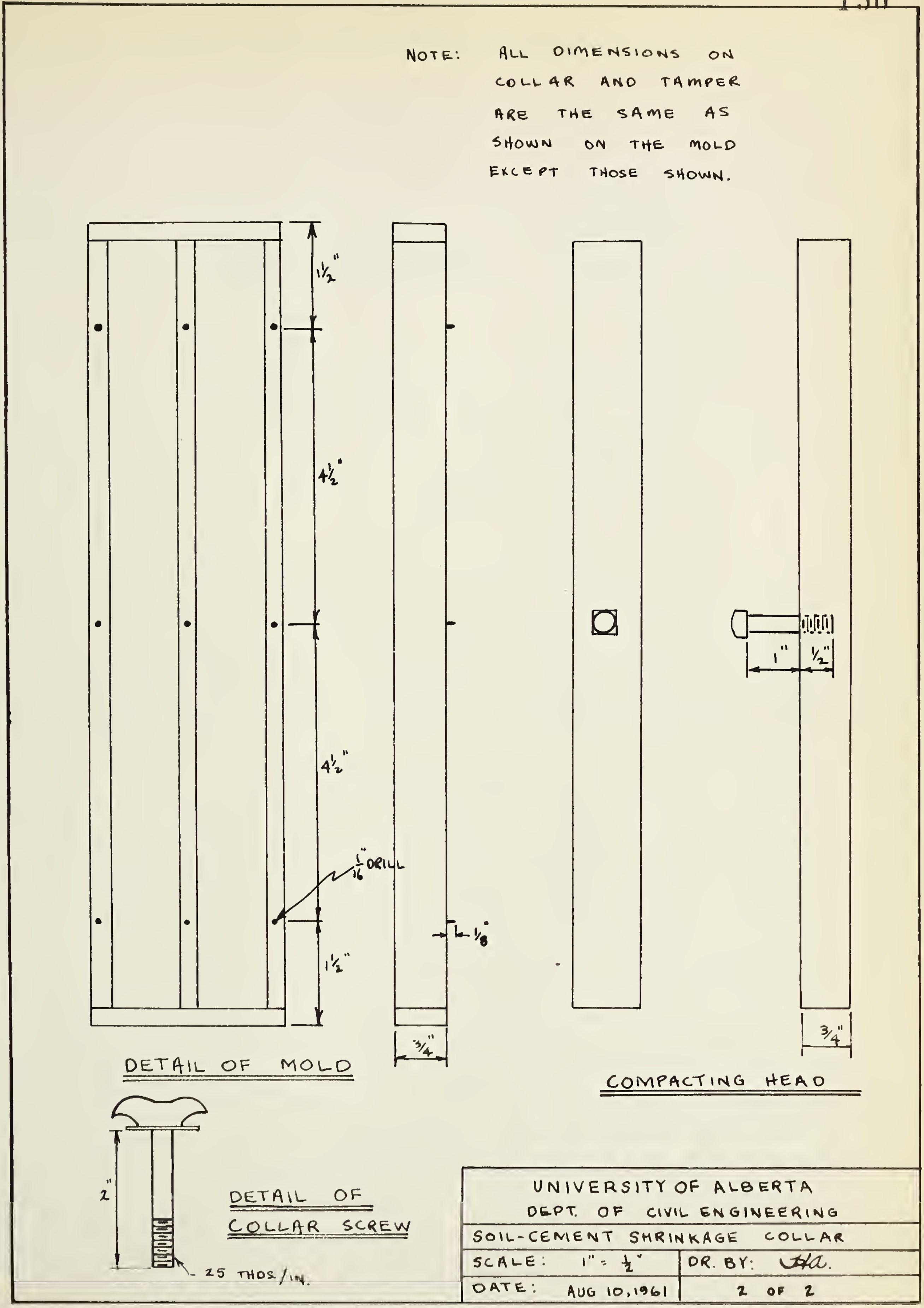
SOIL-CEMENT SHRINKAGE SPECIMEN MOLD

SCALE: 1" = ½"	DR. BY: [illegible]
DATE: AUG 10, 1961	1 OF 2


NOTE: ALL DIMENSIONS ON COLLAR AND TAMPER ARE THE SAME AS SHOWN ON THE MOLD EXCEPT THOSE SHOWN.
1½"
4½"
4½"
1½"
1/16" DRILL
1/8"
3/4"
DETAIL OF MOLD
1"
½"
3/4"
COMPACTING HEAD
2"
25 THOS./IN.
DETAIL OF COLLAR SCREW
UNIVERSITY OF ALBERTA
DEPT. OF CIVIL ENGINEERING
SOIL-CEMENT SHRINKAGE COLLAR
SCALE: 1" = ½"
DR. BY: HA.
DATE: AUG 10, 1961
2 OF 2

APPENDIX D

Sample Data Sheets

[illegible]

[illegible]

SOIL-CEMENT SHRINKAGE DATA

TEST SERIES IB
CEMENT CONTENT 8%
WATER CONTENT 13%
CURING CONDITION S.M.R.
COMPACTION 100% S.P.

SAMPLE NO. 2
WT. CEMENT 23.5
WT. WATER 41.4
WT. SOIL 294.5
COMBINED WT. 359.4

MOISTURE CONTENT DETERMINATION

CONTAINER NO. A17
WET WT.+TARE 127.976
DRY WT.+TARE 121.075
WT. WATER 6.901
TARE 70.307
DRY WT. 50.768
MOISTURE % 13.5 %

DRY DENSITY (EST.) 107.0
CENTER PT. DEFL.(E_f) a 0.49 b 0.39

DRY DENSITY (ACT.) a 109.2 b 107.4
TIME OF MIXING 10:00

SHRINKAGE MEASUREMENTS

DATE	GAUGE	(a)	(b)	DATE	GAUGE	(a)	(b)
JUNE 10, 1000	4060	3197	3301	23, 1330	4060	2971	3079
12, 1330	4059	3106	3181	26, 1130	4058	2965	3069
13, 1330	4058	3071	3151	27, 1100	4061	2977	3083
14, 1330	4060	3040	3127	28, 1100	4061	2964	3074
16, 1330	4058	3024	3117	29, 1300	4060	2967	3076
19, 1100	4061	2988	3091	30, 1330	4060	2968	3078
21, 1350	4061	2980	3085	JULY 4, 900	4059	2913	3020

MIX
S 700
C 56
W 98.2

SOURCE: CAYWOOD

DATE PLACED IN OVEN: JULY 1

TOTAL SHRINKAGE IN/IN: a 284
b 281
av. 282

SOIL-CEMENT SHRINKAGE DATA

TEST SERIES I B
CEMENT CONTENT 7 %
WATER CONTENT 10.4 %
CURING CONDITION SMR
COMPACTION 100 % S.P.

SAMPLE NO. 2
WT. CEMENT 22.6
WT. WATER 36.0
WT. SOIL 323.4
COMBINED WT. 382.0

MOISTURE CONTENT DETERMINATION

CONTAINER NO. A 26
WET WT.+ TARE 112.474
DRY WT.+ TARE 107.860
WT. WATER 4.608
TARE 62.850
DRY WT. 45.016
MOISTURE % 10.2 %

DRY DENSITY (EST.) 117 lb/ft.^{3}
CENTER PT. DEFL.(E_f) a — b 0.47

DRY DENSITY (ACT.) a 118.7 lb/ft^3 b 119.0 lb/ft^3
TIME OF MIXING 10:30

SHRINKAGE MEASUREMENTS

DATE	GAUGE	(a)	(b)	DATE	GAUGE	(a)	(b)
JUNE 3, 1200	4062	3105	3430	12, 1330	4059	2990	3308
4, 1200	4054	3040	3372	13, 1330	4059	2992	3312
5, 1400	4058	3019	3348	15, 1400	4059	2986	3313
6, 1100	4058	3008	3334	19, 1130	4061	2987	3321
7, 1300	4058	2998	3317	21, 1300	4061	2989	3325
8, 1330	4058	2997	3309	23, 1300	4061	2986	3318
9, 1330	4058	2997	3315	25, 1300	4058	2959	3279

MIX:
S 750
C 52.5
W 83.5

SOURCE: HENNIG PIT

DATE PLACED IN OVEN: JUNE 24

TOTAL SHRINKAGE IN/IN: a 14.2
b 14.7
av. 14.4

SOIL-CEMENT SHRINKAGE DATA

TEST SERIES IB

CEMENT CONTENT 8 %

WATER CONTENT 8 %

CURING CONDITION SMR

COMPACTION 100 % S.P.

SAMPLE NO. 2

WT. CEMENT 25.2

WT. WATER 27.2

WT. SOIL 314.8

COMBINED WT. 367.2

MOISTURE CONTENT DETERMINATION

CONTAINER NO. A25

WET WT.+ TARE 131.505

DRY WT.+ TARE 126.500

WT. WATER 5.005

TARE 60.608

DRY WT. 65.892

MOISTURE % 7.6 %

DRY DENSITY (EST.) 115 lb/ft.^{3}

CENTER PT. DEFL. (E_f) a 0.87 b 0.55

DRY DENSITY (ACT.) a ____ b ____

TIME OF MIXING 9:30

SHRINKAGE MEASUREMENTS

DATE	GAUGE	(a)	(b)	DATE	GAUGE	(a)	(b)
JUNE 24, 1100	4060	3311	3316	JULY 4, 1130	4068	3284	3294
24, 1700	4060	3306	3313	6, 1100	4061	3283	3291
25, 1500	4066	3306	3312	7, 1100	4061	3280	3289
26, 1130	4058	3299	3309	10, 1100	4060	3274	3289
27, 1130	4060	3298	3310	13, 1330	4061	3276	3287
28, 1100	4060	3291	3301	15, 0900	4060	3274	3285
30, 1330	4060	3290	3302	17, 830	4060	3254	3268

MIX:

S 750

C 60

W 64.7

SOURCE: SHEPERT

DATE PLACED IN OVEN: JULY 15

TOTAL SHRINKAGE IN/IN: a 57

b 47

av. 52

APPENDIX E

Sample calculations for measurement of shrinkage mix proportioning, and density determinations, determination of E, and thermal coefficients.

Sample Calculations

Measurement of Shrinkage

Sample Specimen   Hennig Pit - IB2

Dial micrometer readings for measurements taken immediately after specimens were removed from the mold and after oven drying.

		Dial Micrometer readings		Change in Length
		Initial	Final	IN x 10^4
Length Comparator	-	4062	4058	- 4
Specimen (a)	-	3105	2959	- 146
Specimen (b)	-	3430	3279	- 151

Corrected values of shrinkage for length comparator

$a = 146 - 4 = 142 \times 10^{-4}$ IN.

$b = 151 - 4 = 147 \times 10^{-4}$ IN.

Unit shrinkage

(a) = 1420 millionths

(b) = 1470 millionths

average (a)&(b) = 1445 millionths

Sample Calculations

Mix proportioning

Example - Hennig Pit Specimen IB2

Volume of mold = 11.25 x 1 x 1 = 11.25 IN^3

Desired Dry Density = 117lbs/FT^3

Dry Wt. Soil + Cement required =

$$\frac{117}{1728} \times 11.25 \times 454 = 346 \text{ grams.}$$

Cement Content = ...7%

Wt. of Cement = $346 - \frac{346}{1.07} = 22.6$ grams.

Wt. of Soil = 346 - 22.6 = 323.4 grams.

Water Content = 10.4%

Wt. of Water = .104 x 346 = 36.0 grams.

Combined Wt. for Mold = 22.6 + 323.4 + 36.0 = 382.0 grams.

Mix

Soil = 750 grams

Cement = 0.07 x 750 = 52.5 grams.

Water = .104 x (750 + 52.5) = 83.5 grams.

Density Determinations

Specimens were broken into three portions of approximately equal length to give an average value of density through the specimen length.

Example Hennig Pit Specimen IA2 (a).

		Left	Center	Right	
Dry Wt.	-	92.5	116.3	94.6	grams.
Wt.Hg. + Tare	-	771.5	941.5	775.0	grams.
Tare	-	107.9	107.9	107.9	grams.
Wt.Hg.	-	663.6	833.6	667.1	grams.

Volume of mercury = $\frac{663.6}{13.55}$ $\frac{833.6}{13.55}$ $\frac{667.1}{13.55}$

Dry Density Left Portion = $\frac{92.5 \times 13.55}{663.6} \times 62.4 = 118\,{}^{lbs}/_{FT^3}$

Dry Density Center Portion = $\frac{116.3 \times 13.55}{833.6} \times 62.4 = 118.2\,{}^{lbs}/_{FT^3}$

Dry Density Right Portion = $\frac{94.6 \times 13.55}{661.1} \times 62.4 = 119.9$

$$\text{Average} = \frac{356.1}{3} = 118.7\,{}^{lbs}/_{FT^3}$$

PERCENTAGE ERROR IN MIX PROPORTIONING, MOISTURE CONTENT AND DENSITY DETERMINATIONS.

Mix Proportioning

Example - Hennig Pit Specimen IB 2.
Mold dimensions are accurate to ± .01 IN.
All tares are accurate to ± .05 grams.

$$\text{Volume of mold} = (11.25 \pm .01)(1 \pm .01)\ 1 \pm .01)$$
$$= (11.25 \pm .1\%)(1 \pm 1\%)(1 \pm 1\%)$$
$$= 11.25 \pm 2.1\%$$

Dry Wt. of Soil + Cement required =

$$\frac{117}{1728} \times 11.25 \pm 2.1\% \times 454 = 346 \pm 2.1\% \text{ grams}$$

Therefore the probable error in the dry density = ±2.1% due to mix proportioning.

Moisture Content Determination.

All tares are accurate to ± .002 grams.

Wet Wt. + tare	=	112.474 ± .002
Dry Wt. + tare	=	107.860 ± .002
Wt. Water	=	4.608 ± .004
Tare	=	62.850 ± .002
Dry Wt.	=	45.016 ± .004

$$\% \text{ Moisture} = \frac{4.608 \pm .004}{45.016 \pm .004} = \frac{4.608 \pm .1\%}{45.016 \pm .01\%} = .102 \pm .11\%$$

Percentage error in moisture content determinations $= \pm 11\%$

Density Determinations

All tares are accurate to $\pm .05$ grams.

Example Hennig Pit Specimen IA2a, Left portion.

Dry Wt. $= 92.5 \pm .05$

Wt. Hg.+ Tare $= 771.5 \pm .05$

Tare $= 107.9 \pm .05$
Wt. Hg. $= 663.6 \pm .1$

$$\text{Dry Density Left Portion} = \frac{92.5 \pm .05 \times 13.55}{663.6 \pm .1} \times 62.9$$

$$= \frac{92.5 \pm .05\% \times 13.55}{663.6 \pm .02\%} = 118 \pm .07\%$$

Percentage error in density determination $= \pm .07\%$

SAMPLE CALCULATIONS FOR THE DETERMINATION OF E

Basic Equation - $\delta = \dfrac{Pl^3}{48\ EI}$

Sample Specimen - Hennig Specimen IB 2 (b)

Load - grams	Deflection - IN.x 10^5
101.82	0
301.82	0
501.82	20
701.82	65
901.82	100
1101.82	130

$$E = \frac{Pl^3}{48 \delta I}$$

$P = 1101.82$ grams

$l = 10$ in.

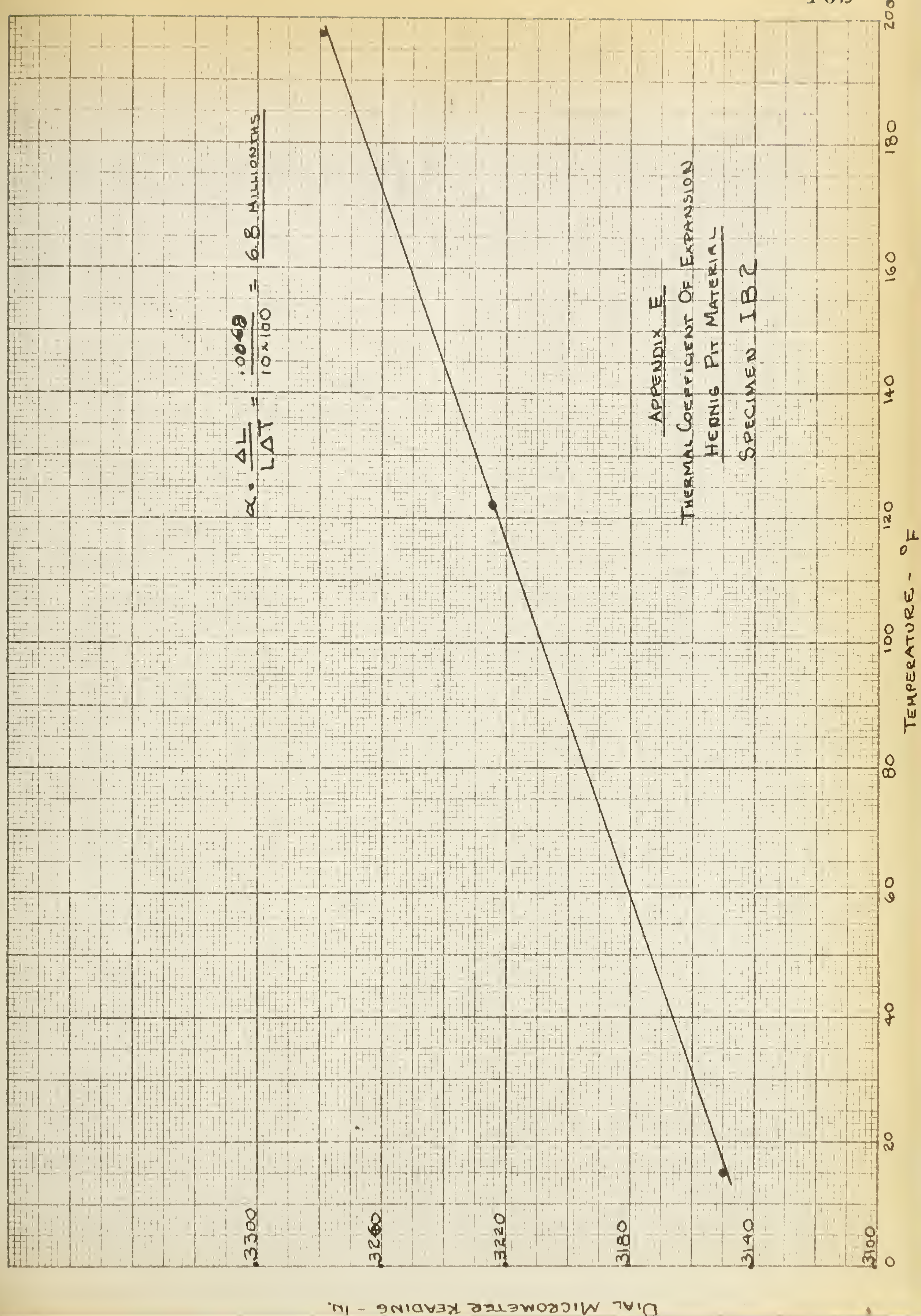
$I = \dfrac{1}{12}$ in.^{4}

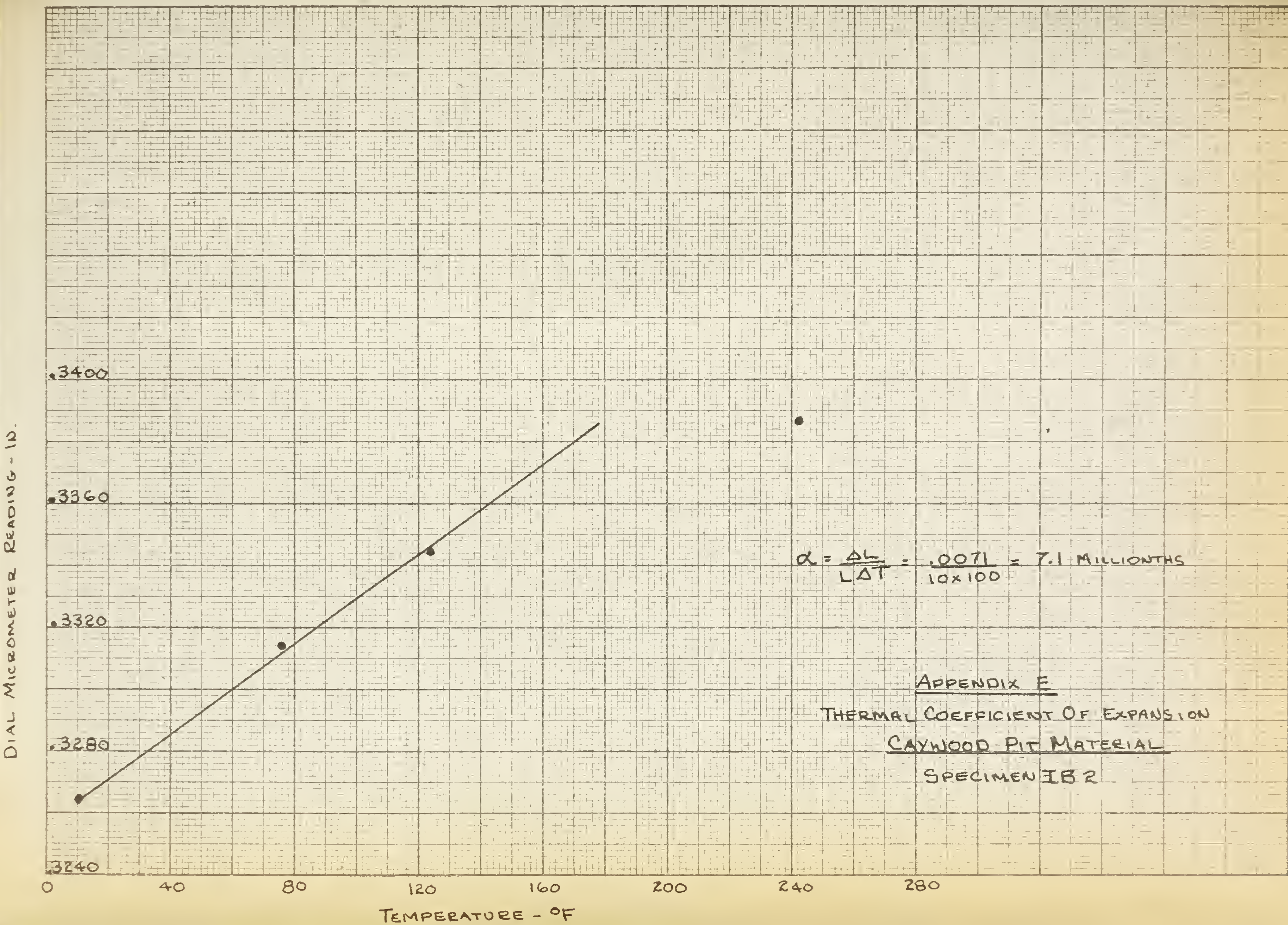
$$E = \frac{\dfrac{1101.82 \times 1000}{454}}{48 \times \dfrac{1}{12} \times \delta} \quad \text{psi}$$

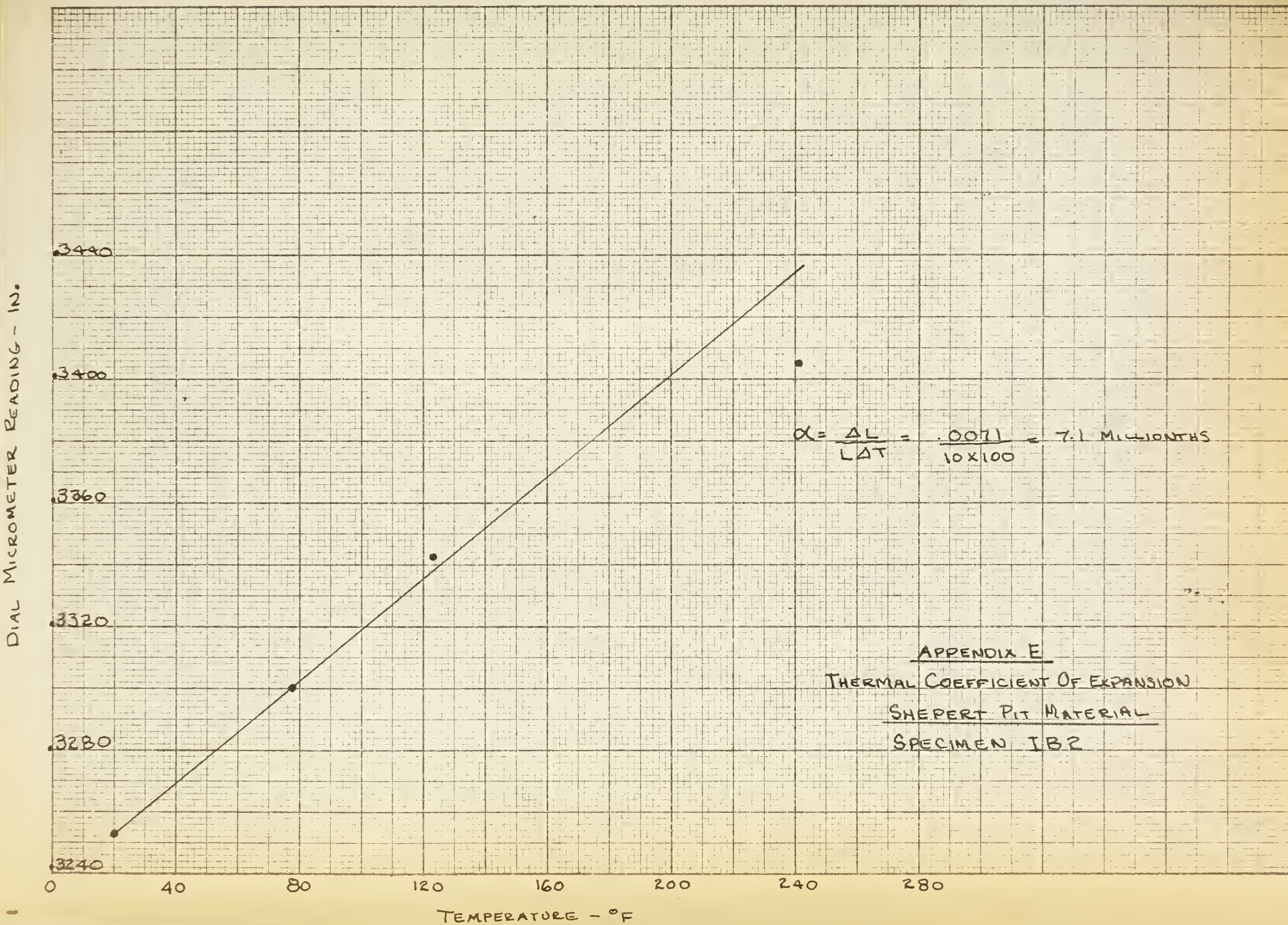
$$E = \frac{607.5}{\delta}$$

For $\delta = 130 \times 10^{-5}$

$$E = \frac{607.5 \times 10^5}{130} = .47 \times 10^6$$


α = ΔL/LΔT = .0068/10×100 = 6.8 MILLIONTHS
APPENDIX E
THERMAL COEFFICIENT OF EXPANSION
HEDNIG PIT MATERIAL
SPECIMEN IB2
TEMPERATURE - °F
0
20
40
60
80
100
120
140
160
180
200
DIAL MICROMETER READING - IN.
.3100
.3140
.3180
.3220
.3260
.3300


.3400
.3360
.3320
.3280
.3240
DIAL MICROMETER READING - IN.
0
40
80
120
160
200
240
280
TEMPERATURE - °F
$\alpha = \frac{\Delta L}{L \Delta T} = \frac{.0071}{10 \times 100} = 7.1$ MILLIONTHS
APPENDIX E
THERMAL COEFFICIENT OF EXPANSION
CAYWOOD PIT MATERIAL
SPECIMEN IB 2


.3440
.3400
.3360
.3320
.3280
.3240
0
40
80
120
160
200
240
280
Dial Micrometer Reading - In.
Temperature - °F
$\alpha = \frac{\Delta L}{L \Delta T} = \frac{.0071}{10 \times 100} = 7.1$ Millionths
Appendix E
Thermal Coefficient Of Expansion
Shepert Pit Material
Specimen IB2

APPENDIX F

The Relationship Between Lineal Shrinkage
and a Simplified Grading Modulus For
the Three Soil-Cements Investigated.

CALCULATIONS OF GRADING MODULUS

<u>Basic Equation.</u>[1]

$$G = \frac{6(1/D_1 - 1/D_2)}{\log_e (D2/D1)}$$

where

G = the grading modulus

D_1 and D_2 = the diameters of the smallest and largest equivalent-size spheres of the size group which just passes sieve size D_2 and is just retained on sieve size D_1

<u>Simplifying Assumption</u>

The grading modulus of that portion of the material which is smaller than 0.05 mm is equal to twice the grading modulus for that portion which passes the No.200 mesh sieve and is larger than 0.05 mm.

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[1]Hughes, B.P., "Rational Concrete Mix Design" Proceedings of the Institution of Civil Engineers (London) Nov. 1960. Vol. 17.

Sample Calculation.

Grading modulus for No. 4 to No.10 sieve.

D_1 = No.10 sieve mesh opening = .079 in.

D_2 = No. 4 sieve mesh opening = .185 in.

$$G = \frac{6\left(\frac{1}{.079} - \frac{1}{.185}\right)}{\log_e \frac{.185}{.079}}$$

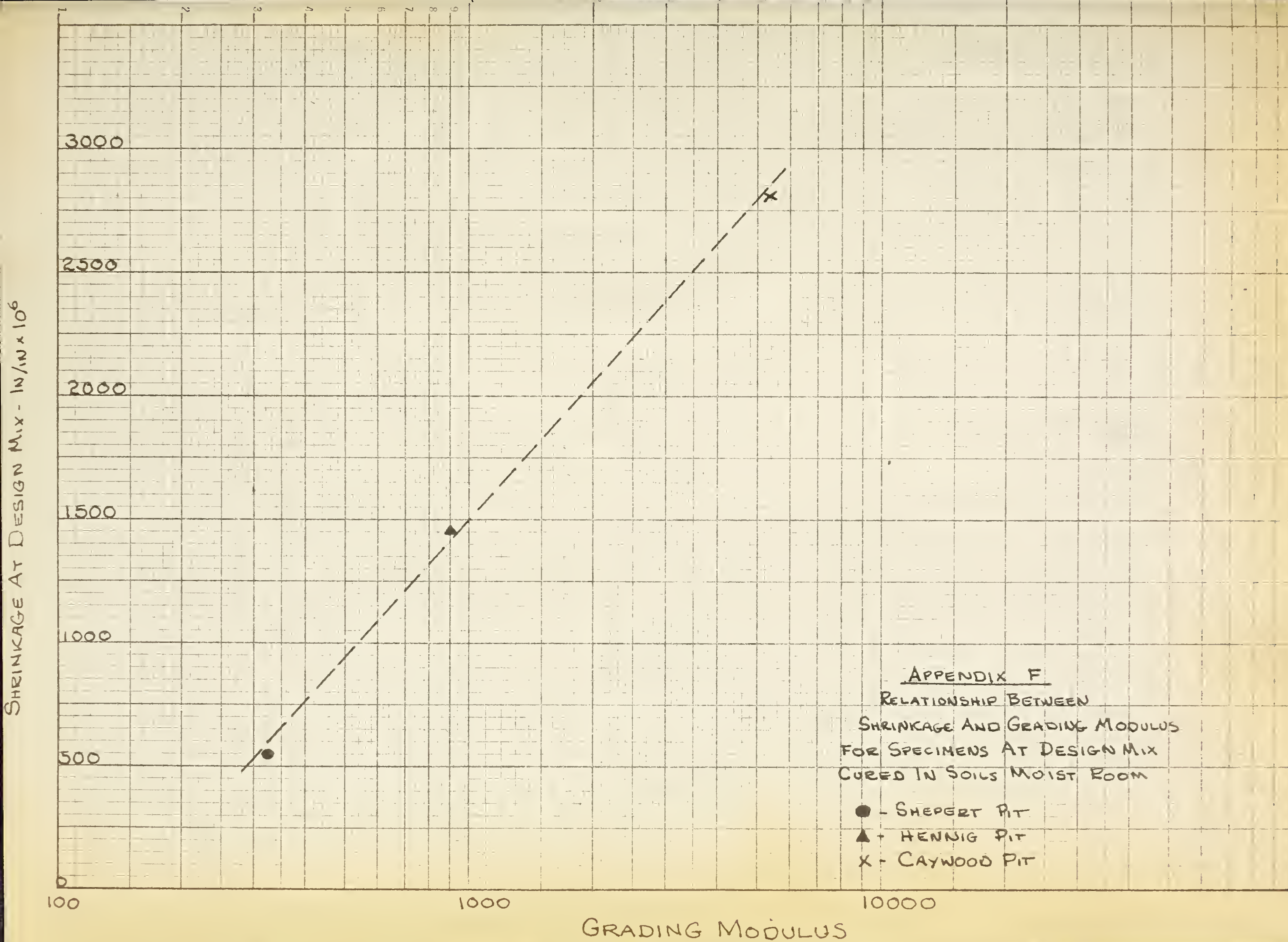
$G = 51.5$

Sieve No.	Grading Modulus
4	
	51.5
10	
	121
20	
	263
40	
	480
60	
	805
100	
	1490
200	
	2980
.05 mm	
	4600
below .05 mm	
	8200

The grading modulus of the aggregate is obtained by multiplying the percent retained on each sieve by the appropriate values as shown above. The sum of these products is then divided by 100 to give the aggregate grading modulus.

Aggregate	Grading modulus
Hennig Pit	900
Caywood Pit	5350
Shepert Pit	330

The following graph shows the relationship between lineal shrinkage of the specimens at the design mix, which were cured in the soils moist room, and the grading modulus determined as above, on a semi-log plot.


Appendix F
Relationship Between
Shrinkage And Grading Modulus
For Specimens At Design Mix
Cured In Soils Moist Room
● - Shepert Pit
▲ - Hennig Pit
X - Caywood Pit
Shrinkage At Design Mix - In/in x 10^6
3000
2500
2000
1500
1000
500
0
100
1000
10000
Grading Modulus